PROVENANCE OF TRIASSIC AND JURASSIC SANDSTONES IN THE BANDA ARC: PETROGRAPHY, HEAVY MINERALS AND ZIRCON GEOCHRONOLOGY

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A B S T R A C T

Quartz-rich sandstones in the Banda Arc Islands are thought to be equivalent of Mesozoic sandstones on the Australian NW Shelf where they are important proven and potential reservoirs. Previous studies suggested that rivers draining Australia provided most of the sediment input and there have been suggestions of a northern provenance for some Timor sediments. We present results from a provenance study of Triassic and Jurassic sandstones of the Banda Arc between Timor and Tanimbar, which used several methodologies, including conventional light and heavy mineral point-counting, textural classification, and laser ablation (LA-ICP-MS) U-Pb dating of detrital zircons. Most sandstones are quartz-rich and detrital modes suggest a recycled origin and/or continental affinity, consistent with an Australian source. However, many of the sandstones are texturally immature and commonly contain volcanic quartz and volcanic lithic fragments. In the Tanimbar Islands and Babar, acid igneous material came from both the Australian continent and from the Bird's Head whereas sandstones in Timor have a greater metamorphic component. Heavy mineral assemblages are dominated by rounded ultra-stable minerals, but mixed with angular grains, and indicate an ultimate origin from acid igneous and metamorphic sources. Detrital zircon ages range from Archean to Mesozoic, but variations in age populations point to differences in source areas along the Banda Arc both spatially and temporally. Significant zircon populations with ages of 240-280 Ma, 1.5 Ga and 1.8 Ga are characteristic and are also common in many other areas of SE Asia. We interpret sediment to have been derived mainly from the Bird's Head, Western and Central Australia in the Triassic. In the Jurassic local sources close to Timor are suggested, combined with recycling of NW Shelf material.

1. Introduction

The Banda Arc Islands Timor, Babar and Tanimbar are situated in eastern Indonesia between Australia, New Guinea and Sulawesi (Fig. 1A). They have been elevated as a result of on-going convergence and subduction processes. Many of the exposed rocks (Fig. 1B) are the equivalents of offshore formations along the NW Shelf of Australia that contain important hydrocarbon reservoirs (e.g. the Jurassic Plover Formation).

It has been generally assumed that during the Mesozoic large rivers drained the Australian continent, large fluvio-deltaic systems filled the major offshore basins of the NW Shelf, and that most sandstones south of Timor contain sediment delivered from those rivers draining northern Australia. Bishop (1999) suggested that marine sandstone reservoirs and deltaic mudstones of the Jurassic Plover Formation were deposited within a fluvial to marginal marine setting. Barber et al. (2003) proposed that sediment was transported to the offshore Jurassic Plover Formation (Fig. 1B**)** from Australia. It was suggested that material was delivered via the Goulburn Graben, and sediment fans reached the Malita Graben and Calder Graben (Fig. 1A**)**. However, these interpretations of lithologies and environments are based on data from a small number of wells over a distance of 500 km.

Further west, Southgate et al. (2011) and Lewis and Sircombe (2013) suggested mainly Australian continental sources for the Mungaroo Formation (Exmouth Plateau: based on wells Guardian-1, Noblige 1, Dalia South 1, Hijinx-1 and Alaric 1; Rankin Plateau: based on wells Goodwyn 6, Lady Nora 2 and North Rankin 5) and the Brigadier Formation (Rankin Plateau: based on wells Dockrell 2 and North

Rankin 5) in the Carnarvon Basin, based on detrital zircon geochronology. The main sediment transport directions for Precambrian material were suggested to have been from south to north via the Perth and Canning Basin with possible sources in Australia, parts of Antarctica and India (Lewis and Sircombe, 2013). Triassic detrital zircons were discovered that were assumed to come from a volcanic province to the south, possibly in the southern Carnarvon, Perth Basin, Antarctica or Greater India.

Little attention has been given to the sources of clastic sediment in the Outer Banda Arc islands. The earliest studies suggested both an Australian source and a northern source for some Triassic sandstones on Timor, mainly based on paleocurrent analyses and heavy mineral data (Bird and Cook, 1991). Some studies including U-Pb zircon geochronology investigated the provenance of Triassic clastic sediments on the islands of Timor, Savu and Kisar in the Banda region (Zobell, 2007; Kwon et al., 2014; Spencer et al. 2015). Further studies have been done on metamorphic complexes, such as the Lolotoi and Aileu complex (Ely et al. 2014; Park et al., 2014; Spencer et al. 2015).

This paper reports the results of a new provenance study in the region. We have analysed petrological features (textures and modal compositions of 40 samples), heavy mineral assemblages of 33 samples, and U–Pb ages of detrital zircons from 24 samples (2540 concordant grains) from sandstones, siltstones and meta-sandstones along a length of 1400 km within the Banda Outer Arc islands.

2. Geological background

The Outer Arc islands include Mesozoic sedimentary, metamorphic and volcanic rocks (Hamilton, 1979). The structure, sequences of siliciclastic sedimentary rocks, and fossil assemblages vary considerably from island to island. A simplified stratigraphy showing formations investigated is presented in Fig. 1B. Lithologies are mainly siliciclastic and calcareous sedimentary rocks that were subsequently uplifted due to Neogene collision of the Banda Arc with the north Australian margin.

Different tectonic models have been developed to account for the origin and history of the region with major controversies between different authors. Numerous authors have favoured an autochthonous Australian margin origin for the Outer Banda Arc islands, and considered the Bird's Head region as a continental peninsula (Hamilton, 1979; Audley-Charles, 1965; Metcalfe, 1996; Charlton, 2001; Hill and Hall, 2003; Baillie et al., 2004). The Banda embayment (Charlton, 2001) was interpreted as an oceanic embayment surrounded by a passive continental margin (Hall et al., 2011) and present-day Timor, Babar, Tanimbar, Seram and SE Sulawesi were suggested to be located within this margin (Audley-Charles, 1965). In comparison, other authors have interpreted the Bird's Head as an allochthonous fragment that rifted from the eastern Australian margin (Pigram and Panggabean, 1984; Pigram and Symonds, 1991; Struckmeyer et al., 1993).

Timor consists predominantly of Mesozoic sedimentary rocks (Permian to Cretaceous) with a Cenozoic cover. Wanner (1913) described the folded lithologies and klippen that are exposed all over the island as complex and difficult to unscramble. The Triassic Niof and Babulu Formations are common in the West Timor Kekneno and Kolbano areas and consist of mudstones, very fine-grained siltstones and well-bedded sandstones. Specimens of *Daonella* indicate a Middle Triassic age (de Roever, 1940). The Niof Formation was identified as Anisian to

Ladinian (Cook, 1987; Bird and Cook, 1991) based on a sparse ammonite and bivalve fauna. The Babulu Formation was dated as Late Triassic (Audley-Charles, 1968; Bird and Cook, 1991; Sawyer et al., 1993) from bivalves, ammonites and palynological data. The Jurassic Wai Luli Formation in West Timor contains light grey mudstones and finely bedded fine-grained siltstones. The Oe Baat Formation contains fine-grained sandstones with conglomeratic layers. Previous authors suggested deposition in the Late Jurassic, based on ammonites (Charlton, 1987; Sawyer et al., 1993).

The island of Babar is a typical but large mud volcano. Fahrizal (1993) described various lithologies and identified Mesozoic shales and erupted fragments. Triassic rocks contain well-bedded thinly laminated grey-green fine-grained sandstones with dark weathering colours. Previous authors suggested deposition in the Late Triassic, based on bivalves and ammonites (van Bemmelen, 1949; Richardson, 1993). Visual and lithological similarities to the Triassic Maru Formation in the Tanimbar Islands suggest a comparable age, and depositional environment. Therefore, Triassic rocks in Babar are here also termed Maru Formation. Jurassic sandstones are limited to central Babar (Suparman et al., 1987) and comprise fine-grained greenish-grey micaceous rocks that are well-bedded and locally contain mud clasts and plant fragments. The unit was dated as Jurassic based on cephalopod faunas (Suparman et al., 1987; Sukamto and Westermann, 1993; Richardson, 1993).

The Tanimbar Islands are interpreted to have been located within northern Gondwana from at least Early Permian times (Charlton, 2012). Charlton et al. (1991) described Upper Triassic to Lower Jurassic rocks which were dated using palynomorphs and later assigned to the Maru Formation (Charlton, 2012). They were found only as blocks ejected from mud volcanoes and include well-bedded sandstones with interbedded siltstone. They were reported (Charlton et al., 1991) to be petrographically similar to the Triassic Babulu Formation in Timor described by Bird and Cook (1991). The Ungar Formation was defined by Charlton et al. (1991) and later reported to include an Arumit Member, a succession of radiolarian claystones interdigitating with the Ungar sandstones. We divide the Ungar Formation into three members: 1) Upper Jurassic Lower Sandstones which contain massive to poorly-bedded, coarse-grained mature quartz sandstones; 2) the Upper Jurassic to Lower Cretaceous Arumit Member which consists of red shale and interbedded red sandstone, mudstone and chert layers that represent a clear marker within the Ungar Formation and yields radiolaria that have been dated by Jasin and Haile (1996) as Upper Jurassic to Lower Cretaceous; and 3) the Lower Cretaceous Upper Sandstone Member, which includes fine to medium-grained arkosic sandstones. The Lower Sandstone Member of the Ungar Formation was undated before this study but suggested to be Jurassic (Charlton et al., 1991). Palynomorph analyses, provided in an unpublished company report (Inpex, pers. comm., 2010) indicated Late Jurassic ages for rocks on the islands close to sampling locations of this study.

3. Methodology

3.1. Petrology

Traditional Gazzi-Dickinson point counting of at least 300 relevant grains of quartz, feldspar and lithic rock fragments (>0.0625mm) was undertaken to acquire light mineral modes used to produce ternary plots for each unit (Dickinson and Suczek, 1979; Dickinson et al., 1983, Ingersoll et al., 1984). The fields in the diagrams for QFL (Quartz-Feldspar-Lithics) and QmFLt (Quartz monocrystalline-Feldspar-Lithic total) have been widely interpreted to indicate possible derivation from ‘continental block’, ‘recycled orogen’ or ‘magmatic arc’ settings. Recent studies have highlighted issues with over-simplified interpretation of these plots when applied in tropical settings (Garzanti et al., 2007; Smyth et al., 2008; van Hattum et al., 2006; Sevastjanova et al., 2012).

Textural categories from 1 to 4 were assigned to sorting and roundness of grains. Sorting categories are (1) poorly sorted, (2) moderately sorted, (3) well sorted and (4) very well sorted. Rounding categories are (1) angular, (2) sub-angular, (3) sub-rounded and (4) rounded. Typical examples of Triassic and Jurassic rocks are shown in Fig. 2.

3.2. Heavy minerals

Detrital heavy minerals were analysed using standard methods described by Mange and Maurer (1992). Samples collected were crushed, decarbonated with 10% acetic acid, sieved and washed (using meshes of 0.063mm and 0.250mm) and separated in a funnel using sodium polytungstate (SPT: $3Na_2WO_4.9WO_3.H_2O$) or the lithium equivalent lithium polytungstate (LST) which have densities between 2.82–2.95 g/ml at room temperature. Identification of heavy minerals was performed manually using an optical polarising microscope (NIKON Eclipse Lv 100) and additional SEM analyses were performed to confirm identification of selected minerals. The ribbon count method used for heavy minerals was described by Galehouse (1971).

Common ultra-stable heavy minerals were categorised into groups corresponding to their most likely protoliths, based on suggested source rocks (Feo-Codecido, 1956; Mange, 2002; Nichols, 2009). Zircon, tourmaline, anatase, monazite, topaz and xenotime are considered to indicate acid igneous (granitic) sources. Pyroxene (Ortho–OPX and Clino–CPX), titanite (sphene) and chromium spinel represent basic igneous and ultrabasic (commonly arc-related) sources. Rutile, garnet, epidote, andalusite, sillimanite, kyanite, chlorite, staurolite and corundum are interpreted to indicate metamorphic sources, mainly of continental character. Other minerals, such as amphibole, baryte, brookite, zoisite, clinozoisite, sphalerite, prehnite, chloritoid, cassiterite, allanite and vesuvianite are present either in very low percentages or can be assigned to more than one group. Apatite is a very common mineral and abundant in all samples of this study (up to 50%). Since it can be found in different groups (acid igneous, granite pegmatite, contact metamorphic and basic igneous), it is treated separately. Typical heavy minerals that are found in the Outer Banda Arc islands are shown in Fig. 3.

Varietal studies of zircon (colourless: euhedral, subhedral, subrounded, rounded, anhedral, elongate, zoned; purple: rounded, idiomorphic; brown, matrix-attached) and tourmaline (brown: rounded, idiomorphic; blue: rounded, idiomorphic; green: all shapes) were performed during counting. Fig. 4 shows example photographs and SEM images of different zircon morphologies. Three groups: 1) euhedral, subhedral, anhedral, elongated and zoned grains were assigned to an ‘idiomorphic’ group; 2) rounded and subrounded zircons form a ‘rounded’ group; 3) grains with matrix attached are the third group. Tourmaline shapes were categorised either as rounded or idiomorphic when they were counted.

3.3. Zircon geochronology

Geochronology using detrital zircons is a powerful method to assess provenance and correlate sedimentary units with identical provenance (e.g. Goldstein et al., 1997; Cawood et al., 1999; Cawood et al., 2003; Fedo et al., 2003; Gehrels et al., 2006; Sevastjanova et al., 2010; Schoene, 2014). The maximum depositional age (MDA) of sedimentary rocks can be determined (Dickinson and Gehrels, 2009) and it is a valuable tool to improve tectonic models and palaeogeographic reconstructions (Murphy et al., 2004).

Selected samples were imaged with scanning electron microscope cathodoluminescence (SEM-CL) at University College London. U-Pb ages were acquired by the author at University College London using Laser Ablation Inductively Coupled Plasma Mass Spectrometry (LA-ICPMS). U and Pb isotopes were analysed, using the following parameters: spot sizes of the ablation pits: 20-35μm; pulse repetition: 8-10Hz; dwell time: 25s; warm-up: 10-15s; wash-out: 18s. The ablated material was carried in helium gas into the plasma. A quadrupole mass spectrometer (Agilent Technologies 7700 Series ICP-MS) was used. Standards that were used were the Plešovice zircon (337.13±0.37 Ma) by Sláma et al. (2008) and a reference glass NIST SRM 612 (Pearce et al., 1997).

Selected zircon assemblages were chosen to investigate the relationship of grain shape (Fig. 4) to the analysed age. The aim was to distinguish optically between rounded grains with recycled histories and idiomorphic grains which could have formed close to the age of deposition. A simplified classification scheme was applied, using CL images of the mounted zircons. Morphologies were subdivided into four groups: 1) euhedral; 2) subhedral; 3) subrounded; 4) rounded.

4. Results

4.1 Light Minerals: Textures and petrography

Fig. 5 shows the results of point counting and textural analysis of sandstones from the various islands (tables in supplementary data 1). In general samples are dominated by quartz with varying concentrations of feldspar and lithic fragments. Sorting and rounding vary between the islands.

4.1.1. Triassic

In West Timor sandstones, the grains are angular to sub-angular and poorly sorted to very well sorted. Compositions are dominated by quartz (43.6-74.8%), feldspar (9.8-35.7%) and lithic fragments (15.2-32.1%) as shown in Fig. 5A. However, there are significant differences between sandstones from the Kekneno and Kolbano areas: Kekneno samples are dominated by monocrystalline and volcanic (Smyth et al., 2008) quartz (37% Qm vs 37% Qv vs 26% Qp), whereas the

Kolbano sandstones have higher abundances of polycrystalline quartz (QFL-total: 37% Qp vs 33% Qv vs 30% Qm). Samples plot in the recycled orogen / dissected magmatic arc field on the QFL diagram and within the dissected magmatic arc / transitional-recycled orogen on the QmFLt diagram (Fig. 5A). On the textures plot samples scatter across the immature to mature field boundary (Fig. 5A).

In East Timor compositionally immature sandstones (sub-angular to subrounded/ moderately to well-sorted grains) are characteristic of the Babulu Formation. They contain monocrystalline quartz (85% Qm vs 10% Qp vs 5% Qv), lithic fragments (24-29.8%) and unweathered feldspar grains (max. 12.8%). The moderately immature lithic arenites plot in the recycled orogen (QFL) or mixed magmatic arc (QmFLt) areas, displayed in Fig. 5A.

The Maru Formation in Babar commonly contains material indicating a mixed source. Polycrystalline quartz (44% Qp vs 31% Qv vs 25% Qm) is commonly dominant, and is accompanied by lithic volcanic fragments (7.5-32.6%) and unweathered feldspar grains (P: 0.3-18.211% vs K: 0-14.2%). Volcanic quartz is abundant in all samples. Sandstones are generally moderately immature, lithic-dominated arenites with textures indicating relatively few cycles of reworking. However, the compositions of the samples plot in a recycled orogen field of the QFL diagram (Fig. 5A) and range from lithic recycled, transitional recycled to quartzose recycled in the QmFLt diagram. Volcanic quartz is abundant in all samples and is likely to be derived from a contemporaneous acid igneous source.

Quartz-dominated sandstones are significant rocks in the Triassic of Tanimbar. Textures vary between angular to rounded and poorly to very well sorted. Relative quartz proportions are dominated by monocrystalline quartz (39% Qm vs 31% Qv vs 30% Qp). Lithic fragments (5-17.8%) and feldspar grains (P: 0.2-11% vs K: 4.6-17%)

are common in the Maru Formation. Volcanic quartz is abundant. Sandstones are generally immature lithic to feldspathic arenites. The QFL diagram shows modal compositions suggest a recycled orogen source, whereas on the QmFLt diagram sandstones plot in the dissected/ mixed magmatic arc and quartzose recycled fields (Fig. 5A). Volcanic quartz is abundant and likely to have been derived from a contemporaneous acid igneous source.

4.1.2. Jurassic

The one Jurassic sample from West Timor is a moderately immature (sub-angular and poorly to moderately sorted grains) lithic to feldspathic arenite which contains monocrystalline quartz (49% Qm vs 30% Qv vs 21% Qp), lithic volcanic fragments (17.4%) and unweathered feldspar grains (K: 11% vs P: 6%). Sandstones plot on the QFL diagram within the area of recycled orogen source (Fig. 5B). The QmFLt diagram indicates a mixed magmatic arc affiliation.

Samples from the Jurassic Sandstone Unit in Babar have high abundances of volcanic quartz (44% Qv vs 29% Qp vs 27% Qm) accompanied by lithic fragments (~14%) and feldspar (P: 2.8-6.41% vs K: 4.6-13.2%). Sandstones have an immature recycled character with sub-angular grains and moderate to very well sorted textures. Samples plot in the recycled orogen to transitional recycled orogen / mixed magmatic arc fields (Fig. 5B).

In Tanimbar there is a relative high concentration of rounded monocrystalline quartz (56% Qm vs 27% Qp vs 17% Qv) in the Jurassic Lower Sandstone Member of the Ungar Formation. Lithic fragments (L: 3.9-11.6%) and feldspar (P: 0-5% vs K: 0-

17.6%) are considerably less abundant than in the Triassic Maru Formation. Lithic fragments and volcanic quartz is abundant. Sandstones generally are relatively mature with angular to rounded grains and range from poorly sorted to very well-sorted. The QFL diagram indicates a recycled orogen / quartzose source, and the QmFLt diagram a dissected to mixed magmatic arc provenance (Fig. 5B).

4.2. Heavy minerals and their protoliths

Heavy minerals from the Banda Arc Islands are generally ultra-stable minerals zircon and tourmaline, accompanied by apatite, garnet, with subordinate andalusite, chlorite and minor pyroxene (tables in supplementary files 2). Fig. 6 shows an overview of heavy minerals, interpreted protoliths and varietal morphology studies.

4.2.1. Triassic

The Niof Formation in West Timor contains a strong metamorphic signal (46%), based on the abundance of andalusite and chlorite (Fig. 6A). The Babulu Formation in the Kolbano area contains, on average, 37% metamorphic, 16% acid igneous and 16% basic igneous grains. The metamorphic signal is due to garnet and chlorite. There is a mixture of rounded zircon (36%) and tourmaline (37%) as well as idiomorphic grains (zircon: 19%; tourmaline: 63%). 20% of zircon grains are attached to a matrix. It is striking that matrix-attached zircon grains are dominant in the

Kekneno area, whereas in the Kolbano area a mix of rounded and idiomorphic zircons predominates.

In the East Timor sandstones, heavy minerals include a mixture of grains (Fig. 6A) with metamorphic (32%) and acid igneous character (28%). Zircon varieties are predominantly idiomorphic (43%), matrix-attached (33%) and rounded (25%). Tourmalines are dominated by idiomorphic grains (77% idiomorphic vs 23% rounded). Metamorphic minerals are predominantly garnet and rutile (ET 11 and ET 16), and garnet, andalusite and epidote (ET 09). ET 09 differs significantly from ET11 and ET16 with a low zircon and tourmaline content, but high apatite and Cr spinel content.

Heavy minerals from Babar sandstones consist on average of 49% acid igneous/sedimentary (zircon, tourmaline), 17% metamorphic (rutile, garnet, minor Al-silicates) and 7% basic igneous/ultramafic (pyroxene and Cr-spinel) grains (Fig. 6A). Zircon shapes are dominantly idiomorphic (50%) with 40% rounded grains and 10% matrix-attached. Tourmaline morphologies are dominated by idiomorphic grains (69%) accompanied by 31% rounded.

Heavy minerals from Tanimbar sandstones consist on average of 49% acid igneous/sedimentary, 21% metamorphic (garnet, rutile and minor andalusite) and 9% basic to intermediate igneous grains, mainly indicated by ortho- and clinopyroxene (Fig. 6A). Morphologies of zircons are dominantly idiomorphic (53% idiomorphic vs 37% rounded vs 10% matrix-attached). Tourmalines are 80% idiomorphic and 20% rounded and are brown (78%), blue (9%) and green (13%). In general, samples are compositionally and texturally very similar to Triassic samples from Babar.

4.2.2. Jurassic

Grains in West Timor sandstones are 43% metamorphic origin (indicative minerals are garnet, andalusite and chlorite), suggesting medium grade contact and regional metamorphic sources (Fig. 6B). The acid igneous minerals contribute on average 21% and the basic igneous 2%. Morphologies are clearly dominated by idiomorphic zircon (~67%) and tourmaline (~67%) grains. A contemporaneous igneous source is interpreted for the Jurassic in West Timor, mixed with metamorphic input.

In Babar, BAB 34 and BAB 35 yielded different abundances of heavy minerals. BAB 34 appears similar to other Jurassic samples in West Timor and Tanimbar, and is dominated by 69% acid igneous/sedimentary and 26% metamorphic grains (Fig. 6B). Morphologies of zircons (66% rounded vs 34% idiomorphic) and tourmaline (62% idiomorphic vs 38% rounded) are dominated by rounded grains. BAB 35 in comparison consists of 20% acid igneous/sedimentary, 9% metamorphic and 40% basic/intermediate igneous (mainly OPX) grains. Morphologies of zircons are dominated by idiomorphic grains (53% idiomorphic, 31% rounded and 16% matrix-attached). Tourmalines are 74% idiomorphic and 26% rounded.

Heavy minerals from Tanimbar samples consist on average of 77% acid igneous/sedimentary, 11% metamorphic and 2% basic igneous to intermediate grains (Fig. 6B). Morphologies of zircon are dominated by rounded grains (74% rounded vs 25% idiomorphic vs 1% matrix-attached). Tourmalines are 88% rounded and 12% idiomorphic and are brown (67%), blue (30%) and green (3%). The predominance of rounded zircon and tourmaline is characteristic of the Lower

Sandstone Member of the Ungar Formation. In contrast to the Triassic Maru Formation, metamorphic and contemporaneous igneous grains are less abundant. The Arumit Member sandstones consist of 25% acid igneous/sedimentary, 19% metamorphic (garnet, epidote, sillimanite) and 2% basic igneous to intermediate grains. The heavy minerals are dominated by apatite (41%). Morphologies of zircon are idiomorphic (47%), rounded (29%) and matrix-attached (24%). Tourmalines are 85% idiomorphic and 12% rounded with brown (56%), blue (38%) and green (6%) colours.

4.3. Zircon geochronology features

Data tables of LA-ICP-MS analyses can be downloaded from the supplementary data 3 which contains $^{207}Pb/^{235}U$ ratios, $^{206}Pb/^{238}U$ ratios, calculated ages and preferred ages, considering exclusion of discordant grains**.** The numerical ages assigned here to periods, epochs and stages are based on Gradstein et al. (2012).

4.3.1. Triassic

A total of 1755 concordant zircon analyses from Triassic sandstones were obtained. Histograms of detrital zircon ages and grain morphologies from Triassic formations in the Banda Arc are notably similar (Fig. 7), with comparable proportions of 4000-541 Ma Precambrian (38-44%) to 541-0 Ma Phanerozoic (56-62%) grains.

In West Timor the Niof Formation (176 concordant zircon analyses from samples SZ 07, SZ 17) was previously suggested to be Anisian to Ladinian (Cook, 1987). The youngest zircon ages constrain the maximum depositional age (MDA) to Carnian (230.5 ±4.2 in SZ 7) and Ladinian (237.2±4.1 in SZ 17). The youngest zircon ages of the Late Triassic (Bird and Cook, 1991) Babulu Formation (316 concordant zircon analyses from samples SZ 41, SZ 48 and SZ 49) constrain the maximum depositional ages to Rhaetian (208.1±2.3 Ma in SZ 41) and Norian (217.1±2.5 in SZ 48 and 209.5±4.4 in SZ 49). Triassic samples in West Timor contain zircons with 57.3% Phanerozoic, 40.2% Proterozoic and 2.4% Archean ages. Most abundant age populations (Fig. 7A) are Permian-Triassic (29.1%), Cambrian to Carboniferous (28.3%) and Paleoproterozoic (20.5%). The main peaks are at 250, 320, 500, 1200, 1600 and 1800 Ma. Zircon grain morphologies of Permian-Triassic age are dominated by euhedral and subhedral grains, Cambrian to Carboniferous are subrounded/rounded to subhedral and Proterozoic zircons are mainly rounded and subrounded (Fig. 7B).

In East Timor samples contain 237 concordant zircon grain analyses from samples ET 11 (MDA: 230.5±3.4 Ma) and ET 16 (MDA: 227.7±2.8 Ma) which constrain the maximum depositional age of the Babulu Formation to the Late Triassic (Carnian-Norian). Age spectra are composed of 57% Phanerozoic, 39.7% Proterozoic and 3.4% Archean ages (Fig. 7A). Most abundant populations are Permian-Triassic (29.5%), Cambrian to Carboniferous (27.4%) and Paleoproterozoic (23.6%). The main peaks are at 230, 330, 550, 1200, 1600 and 1750 Ma. Permian-Triassic zircon grains are subrounded/rounded to subhedral/euhedral, Cambrian to Carboniferous are idiomorphic and Proterozoic zircons are mainly rounded and subrounded (Fig. 7B).

Triassic samples from Babar (BAB 05, BAB 13, BAB 22 and BAB 23) contain 332 concordant zircon analyses and have a youngest zircon age (209.5±3Ma; BAB 05) which indicates a maximum depositional age of Late Triassic (Norian/Rhaetian) for the Maru Formation. This supports previous authors who suggested deposition in the Late Triassic (van Bemmelen, 1949; Richardson, 1993). Samples contain 56% Phanerozoic, 42.5% Proterozoic and 1.5% Archean ages (Fig. 7A). Principal populations are Cambrian to Carboniferous (30.7%), Paleoproterozoic (28.9%) and Permian-Triassic (25.3%).The main peaks are at 230, 270, 320, 370, 1600 and 1800 Ma. Zircon grains of Permian-Triassic ages are euhedral and subhedral, Cambrian to Carboniferous zircons are subrounded/rounded to subhedral/euhedral and Proterozoic zircons are mainly rounded and subrounded with few idiomorphic grains (Fig. 7B).

Triassic samples in Tanimbar were assigned to the Maru Formation. Grouped Triassic samples contain 694 concordant zircon analyses for the samples TAN 06, TAN 09, TAN 13, TAN 24, TAN 26 and TAN 36. A previously suggested Late Triassic to Early Jurassic age (Charlton et al., 1991) is supported by the youngest zircon age (202.2±2.4 Ma; TAN 24) within this group which indicates a maximum depositional age of Late Triassic (Rhaetian). Samples include 62.2% Phanerozoic, 36.5% Proterozoic and 1.3% Archean ages (Fig. 7A). Most abundant age populations are Permian-Triassic (31.3%), Cambrian to Carboniferous (31%) and Paleoproterozoic (25.2%). The main peaks are at 230, 290, 360, 1600 and 1800 Ma. However, samples TAN 06 and TAN 36 are at opposite ends of the ranges for Triassic sandstones and are striking in their contrasting abundances of Phanerozoic and Proterozoic zircons. TAN 36 is dominated by Phanerozoic (84.1% vs. 13.6% Proterozoic vs. 2.3% Archean) whereas TAN 06 is dominated by Proterozoic (67.2%

vs. 31.9% Phanerozoic vs. 0.9% Archean) grains. Zircon grains with Permian-Triassic ages are euhedral and subhedral, Cambrian to Carboniferous zircons are a mix of subrounded/rounded to subhedral/euhedral grain morphologies and Proterozoic zircons are dominated by rounded and subrounded grains (Fig. 7B).

4.3.2. Jurassic

A total of 785 concordant zircon analyses were obtained from Jurassic sandstones. Histograms of detrital zircon ages and zircon grain morphologies for Jurassic formations on different islands in the Outer Banda Arc differ significantly from each other (Fig. 8). Precambrian zircons vary from 1% in West Timor to 96% in Tanimbar.

In West Timor one Jurassic sample (SZ 44) has a youngest zircon age of 148.2±2.1 Ma (MDA) that indicates Latest Jurassic (Tithonian) or younger deposition. It is striking that the clear predominance of Phanerozoic zircon grains (99.2%) consists of 85.9% Jurassic ages **(**Fig. 8A). The second most abundant age group is Permian-Triassic (13.3%). The main peaks are at 160 to 180 Ma. Only one Proterozoic grain was found and there were no Archean grains. Jurassic zircons are dominated by euhedral and subhedral grains and Permian-Triassic zircon populations include a mix of subrounded, subhedral to euhedral grain morphologies (Fig. 8B).

Samples from the Jurassic Sandstone in Babar yielded 259 concordant analyses and a youngest zircon age of 193.4±3 Ma, constraining the maximum depositional age to Early Jurassic (Sinemurian). Age populations are similar to Triassic samples from Babar and also Tanimbar (Fig. 7A). However, there are differences between BAB 34 and BAB 35, shown in Fig. 8A. Zircon ages from BAB 35 are similar to Triassic samples in Babar (and also Tanimbar) with 63.5% Phanerozoic, 35.7% Proterozoic and 0.8% Archean ages. Most abundant age populations are Paleoproterozoic (30.2%) and Permian-Triassic (31.7%). BAB 34 contains zircons with 34.6% Phanerozoic, 62.4% Proterozoic and 3% Archean ages. Most abundant age populations are Paleoproterozoic (34.6%), Mesoproterozoic (20.3%) and Cambrian to Carboniferous (16.5%). Permian-Triassic zircons represent 7.5%. Grains of Jurassic age are euhedral, those with Permian-Triassic ages are mainly euhedral and subhedral, Cambrian to Carboniferous zircons are subrounded/rounded to subhedral/euhedral and Proterozoic zircons are mainly rounded and subrounded. However, the Paleoproterozoic population contains at least one third idiomorphic grains (Fig. 8B).

Jurassic samples from Tanimbar yielded 398 concordant analyses for samples TAN 18, TAN 20, TAN 23 and TAN 30. TAN 18 and TAN 20 were sampled just below the well-dated Arumit Member which contains Upper Jurassic–Lower Cretaceous radiolaria in cherts (Jasin and Haile, 1996). The youngest zircon age (318.1±4 Ma; TAN 30) within the previously undated Lower Sandstone Member of the Ungar Formation indicates a maximum depositional age of Carboniferous (Bashkirian), which is rather unexpected considering the suggested Jurassic depositional age. Samples are strongly dominated by Precambrian zircons (96%) and notably few Phanerozoic (4%) zircons (Fig. 8A). Most abundant age populations are Paleoproterozoic (41.2%), Mesoproterozoic (34.4%) and Neoproterozoic (14.3%). The main peaks are at 350, 900, 1200, 1600, 1800 Ma. Archean (5.5%)

zircons with a peak at 2.5 Ga are also present. Morphologies are dominated by rounded and subhedral grains, subrounded grains are absent (Fig. 8B).

5. Discussion

The samples analysed are mainly quartz-rich sandstones. Light minerals show sandstones have similar compositions in different islands that, according to conventional plots, indicate derivation from a recycled orogen in a continental block setting, with a minor magmatic arc influence. Monocrystalline quartz and lithic volcanic fragments are common and indicate an acid volcanic source. Potassium feldspar also suggests an acid igneous source. Some polycrystalline quartz and plagioclase may indicate metamorphic or arc-related sources. High volcanic quartz proportions are common, and were not previously reported. Textures suggest a mixture of contemporaneous volcanic and poly-recycled input. Compositionally, sandstones are mainly mature, but textures are mainly immature.

Heavy minerals from the Outer Banda Arc Islands are dominated by ultra-stable minerals zircon and tourmaline, accompanied by apatite, garnet, with subordinate andalusite, chlorite and minor pyroxene. Variations between the islands and individual formations indicate changes in provenance, and possibly different sediment transport directions from the Triassic to the Jurassic.

The few studies with detrital zircon age data at the extreme western and eastern ends of the Banda Arc correlated specific zircon age populations with volcanic, metamorphic, sedimentary and meta-sedimentary sources, and interpreted tectonic events. Provenance and geochronology studies by Southgate et al. (2011), and Lewis and Sircombe (2013) using NW Shelf well samples, and Gunawan et al. (2012) in the Bird’s Head (Fig. 9) are a useful guide to some likely sources of siliciclastic sediments in the Outer Banda Arc. Studies of the NW Shelf of Australia (e.g. Sircombe and Freeman, 1999; Bryan et al., 2012) and geochronology-based provenance studies on detrital zircons in the SE Asian region (e.g. Smyth et al., 2003, 2007; Sevastjanova et al., 2011; Clements et al., 2012; Hall and Sevastjanova, 2012; van Hattum et al., 2013; Davies et al., 2014; Hennig et al., 2015) were considered when making interpretations. Fig. 10 shows a map of greater Australia and SE Asia, highlighting the islands investigated and possible main regions (i.e. granitoid bodies, tectonic fragments and cratons) that could have supplied material to the Banda region in the Triassic and Jurassic.

5.1. Origin of Permian-Triassic and Jurassic zircon populations

Permian to Triassic age peaks (Fig. 7A) in samples of this study are c. 260-240 Ma (West Timor and East Timor) and c. 300-260 Ma (Babar and Tanimbar). Permian to Triassic acid volcanic rocks in the Bird’s Head area were identified by Gunawan et al. (2012) as an important contemporaneous source for the Triassic Tipuma Formation (Fig. 9). Acid plutonic igneous rocks now exposed in the Bird’s Head area include the Netoni Intrusive Complex, the Wariki Granodiorite and the Anggi Granite (Pieters et al., 1983; Pieters et al., 1989; Amri et al., 1990; Robinson et al., 1990). These are considered to be plutonic equivalents of the now eroded volcanic rocks. The volcanic material could have been reworked into terrestrial sediments, and transported by rivers before being deposited in a fluviatile to marginal marine setting (Gunawan et al., 2012). Some material could have been transported along the Gondwana margin as volcanic ash in airfall deposits; Triassic zircons in SE Indonesia were suggested to have been derived from airfall from active contemporaneous volcanoes (Sevastjanova et al., 2012), explaining zircons that are still attached to volcanic glass.

For the NW Shelf, Lewis and Sircombe (2013) pointed out that euhedral Triassic grains in the Mungaroo Formation and possible interpreted short transport distances were unexpected. They implied that these could have been related to rifting of the Gondwana margin during the Triassic. Alternatively, we suggest that the very small numbers of Triassic zircons in the NW Shelf samples could have been derived from distal airfall deposits erupted from volcanoes in the Bird's Head. Permian to Triassic zircons in river sediments of Sundaland were suggested to have been derived from the Tin Belt granitoids between the Thai–Malay Peninsula and Sumatra (Hall and Sevastjanova, 2012). Spencer et al. (2015) suggested similar age peaks (Aileu Complex and Babulu Formations in East Timor) of 230–400 Ma were associated with zircons derived from Tibet and Malaysia. However, Tibet or Sundaland are very improbable sources for the NW Shelf and Banda sandstones since they are, and were in the Triassic, so distant from the NW Shelf–Banda region as illustrated by tectonic reconstructions (e.g. Sevastjanova et al., 2015). Permian-Triassic zircons in Triassic to Jurassic sandstones and metamorphic rocks from SE Sulawesi (500-200 Ma) were interpreted by Ferdian et al. (2012) to have been derived from the Banggai-Sula granite (Pigram and Surono, 1985, Ferdian et al., 2012) which belongs to a Permian-Triassic granitoid belt extending from New Guinea to the Sula Spur (Pigram et al. 1984). In the Triassic SE Sulawesi was part of the Sula Spur.

The only Jurassic zircons found in this study are from West Timor samples and have ages of c. 180-160 Ma (Fig. 8A). Jurassic igneous activity has not previously been recorded in the Banda region. Hall and Sevastjanova (2012) reported that Jurassic zircons are uncommon in most parts of Indonesia. Middle Jurassic zircons have been reported from the Mekongga Formation in SE Sulawesi and a 195 Ma zircon age was reported from the Bobong Formation in the Banggai-Sula Islands (Ferdian et al., 2012). These areas would have been part of the Sula Spur but up to now no sources of Jurassic zircons have been identified there. Park et al. (2014) identified Jurassic zircons from the Lolotoi Complex in East Timor in rocks described as andesites. However, photographs and zircon ages from one of their samples (FV27) suggest it to be volcaniclastic sandstone. Volcanic rocks and volcaniclastic sandstones suggest a source on or close to Timor. Jurassic volcanic activity is proposed here to have provided a short-lived source in the Timor sector of the NW Shelf with an age range of 200-150 Ma, associated with the break-up of Gondwana and the subsequent fragmentation and drift of Australian continental blocks.

5.2. Provenance of the Banda Arc sandstones

5.2.1. Triassic

There are clear petrological changes from east to west (Fig. 11). Sandstones contain higher proportions of quartz in the eastern islands of Babar and Tanimbar and increasing feldspar and lithic contents towards West Timor. Volcanic quartz also increases towards the east. Heavy minerals show a greater recycled sedimentary to contemporaneous acid igneous input in the east (Babar and Tanimbar) and a greater metamorphic component in the west (West Timor and East Timor). In Tanimbar it is striking that there is a relative increase of rounding from the southern islet Natraal (1=angular) to the northern island Molu (4=rounded). The feldspar and lithic grain abundances within these samples decrease to the north from the islets Natraal-Vulmali-Ungar-Teineman-Molu (Fig. 1A). In the northern islands (i.e. Molu and Maru) idiomorphic grains and matrix-attached zircons are more abundant than in the south (i.e. Wuliaru and Natraal) where there are more rounded grains. These features could indicate a contemporaneous northern acidic igneous source and transport of poly-recycled material from the south. However, these features could also reflect stratigraphic position of samples which is not well constrained.

Histograms of zircon ages from different islands are very similar to each other and to the Tipuma Formation of the Bird's Head (Fig. 7A and Fig. 9). Samples from the Outer Banda Arc islands and the Bird's Head contain more Phanerozoic than Precambrian zircons (Fig. 7A). In contrast, the NW Shelf of Australia (Rankin Plateau and Exmouth Plateau**;** Fig. 9) sandstones are dominated by Precambrian zircon populations. Archean, Mesoproterozoic and Neoproterozoic grains dominate within the Mungaroo and Brigadier Formations that were suggested to have been sourced from Western Australia via the Proto-Perth Basin (Southgate et al., 2011; Lewis and Sircombe, 2013).

There is an increase in Permian-Triassic zircons and a decrease in Neoproterozoic and Mesoproterozoic zircons from west to east. Paleoproterozoic zircons are not abundant in Precambrian populations of the NW Shelf, but are a significant component in the Bird's Head and the Banda Arc Islands from Tanimbar to Timor, and a strong 1.8 Ga peak is characteristic of the eastern Banda Arc (Tanimbar and Babar) and Bird’s Head area.

In Timor the Paleoproterozoic population peak is broader and includes a strong 1.5 to 1.6 Ga population. Further west, the NW Shelf samples include a moderate number of 1.5 to 1.6 Ga zircons and stronger 1.2 Ga peak. Therefore, Neoproterozoic and Mesoproterozoic zircons are suggested to be sourced from Western Australian cratons, whereas Paleoproterozoic populations were probably sourced from Central Australia and possibly New Guinea. The NW Shelf has a distinctive western Australian character, which includes a significant number of Archean grains. Timor appears to include zircons sourced from both west and east, whereas zircon populations from the eastern islands resemble those of the Bird’s Head.

Quantitative cumulative percentages of grouped zircon populations (by period) for each area between the Bird’s Head and Rankin-Exmouth plateaus highlight likely sources and display the variations from east to west (Fig. 11). Percentages of Permian-Triassic, Carboniferous and Devonian zircons decrease from the Bird’s Head (81%) via the Banda Arc Islands (47-58%) to the Exmouth Plateau (10%) and the Rankin Plateau (3-7%). We interpret these values to indicate that the Bird’s Head region was a major source of acid igneous material to Triassic sandstones in the Outer Banda Arc islands. This included contemporaneous volcanic zircons, as well as Palaeozoic zircons recycled from igneous rocks from a long-lived Andean-type northern New Guinea active margin (Gunawan et al., 2012). Poly-recycled sedimentary material of Precambrian age is suggested to have been mainly derived from Northern/Central Australia. Western Australia is proposed to have supplied material of Precambrian metamorphic origin to Timor. Zircon grain morphologies support these interpretations. Permian-Triassic grains are predominantly idioblastic, suggesting limited recycling and contemporaneous volcanic activity, and are accompanied by a few recycled grains. Cambrian to Carboniferous zircons include rounded and idioblastic grains and suggest a poly-recycling history with minor input from contemporaneous unroofing and erosion of older units. Proterozoic zircons are predominantly rounded (Fig. 7B) indicating abrasion during a complex polycyclic history. However, a few euhedral grains indicate local contemporaneous unroofing of older cratons.

Our new results provide a test of tectonic models that concern the position of the Bird’s Head in the past. Pigram and Panggabean (1984), Pigram and Symonds (1991) and Struckmeyer et al. (1993) proposed that the Bird’s Head is an allochthonous fragment that was situated approximately two thousand kilometers east of its present position close to eastern Papua New Guinea in the Triassic. In contrast, most other authors have favored a position for the Bird’s Head relative to Australia similar to that of the present-day (e.g. Metcalfe, 1996; Charlton, 2001; Hill and Hall, 2003). The new data support the latter interpretation which accounts for the gradual reduction in the Bird’s Head signature seen in zircon ages and volcanic grains from east to west in the Outer Banda Arc islands.

A Triassic palaeogeographic reconstruction with tectonic elements, age provinces and major interpreted sediment transport directions is displayed in Fig. 12. The heavy minerals and detrital zircon ages suggest three principal source areas – Western Australia, Northern/Central Australia and Bird’s Head/Sula Spur. Fig. 13 shows a simplified three-dimensional cartoon of the greater Banda Arc area in the Triassic. Possible depositional environments and facies are shown and locations of potential sources are indicated. The Bird's Head/Sula Spur source also accounts for the proposed northern source for sandstones of Timor (Bird and Cook, 1991).

5.2.2. Jurassic

Siliciclastic Jurassic formations in West Timor, Babar and Tanimbar are significantly different from one another with some unexpected and striking features. Sandstone petrography and heavy mineral assemblages indicate, compositionally and texturally, relatively mature quartz-rich sediments, with zircon morphologies suggesting derivation from sources with a poly-recycled character for Babar and Tanimbar zircons, and a contemporaneous source for West Timor zircons. Fine grained red shales of the Arumit Member of the Ungar Formation (TAN 19) in Tanimbar contain a very small siliciclastic component (so no modal composition could be determined), but at least 4 chert horizons consistent with a low rate of clastic sedimentation in a quiet deep marine setting. The relatively low abundance of ultra-stable heavy minerals and domination of apatite in the very fine-grained Arumit Member shales also supports the interpretation of a deep water environment (Morton, 1986).

Jurassic sandstone zircon populations have many similarities to those of the Triassic sandstones. However, there are significant differences between the islands indicating regional variations in provenance.

A single West Timor Jurassic sandstone contains a dominant Jurassic zircon age peak with a smaller number of Permian and Triassic zircons (Fig. 8A) interpreted to indicate a contemporaneous volcanic source in the Jurassic. Volcanic activity associated with rifting of the southern Banda Block (SW Borneo of Hall et al., 2009, and Hall, 2012), situated to the north of Timor, is proposed. Jurassic zircons are also found in rocks that are interpreted to have been part of blocks rifted from the Banda region including granites of the southern Schwaner Mountains of SW Borneo (van Hattum et al., 2013; Davies et al., 2014) and in granites of the Inner Banda Block (later NW Sulawesi) reported by Hennig et al. (2015). Possible locations of Jurassic volcanic activity are shown schematically in the palaeogeographic reconstruction of Fig. 14.

In contrast, sandstones from the Lower Sandstone Member of the Ungar Formation of Tanimbar contain no Jurassic or Permian-Triassic zircons, but abundant Neoproterozoic, Mesoproterozoic and Paleoproterozoic populations (Fig. 8A). The absence of Jurassic zircons suggests a position further from the site of active rifting than for the Timor sandstones. The Tanimbar Jurassic sandstones contain zircons of mixed provenance indicating Australian sources with minimal influence from the Bird's Head region. The youngest grain is 318.1±3.9 Ma and therefore much older than the depositional age. The most important zircon populations indicate Northern/Central Australia (75.6%) and Western Australia (21.1%) were the main sources. The Bird's Head signal (~3.3%) is surprisingly low with no Permian-Triassic zircon populations. The predominant Proterozoic and Archean ages show striking similarities to the Triassic Brigadier and Mungaroo Formations on the NW Shelf of Australia (Fig. 9). Proterozoic zircons in Tanimbar Jurassic sandstones are mainly rounded indicating multiple recycling (Fig. 8B). The few subhedral first or second cycle zircons (with Paleoproterozoic, Mesoproterozoic and Neoproterozoic ages) could have been derived from nearby basement. Two models can be proposed for the Lower Sandstone Member of the Ungar Formation on Tanimbar: 1) deposition at the present day location above the Triassic Maru Formation with a predominant Australian source, and isolated from the Bird's Head by some geographical barrier, in which case the sandstones are autochthonous; 2) deposition further west in a location similar to sandstones of the NW Shelf of Australia (Brigadier and Mungaroo Formations) followed by a later tectonic displacement, implying the sandstones are part of the Banda Allochthon. The latter would imply a major tectonic junction within the sequence, which is possible because of the incomplete exposure of the Ungar Formation.

Babar Jurassic samples contain material indicating a mixed provenance from Australia and the Bird’s Head region (Fig. 8A) and are suggested to be partly reworked from older Triassic sandstones. Major zircon populations indicate sources in Northern/Central Australia (45.2%), the Bird’s Head (41.3%) and Western Australia (12.7%). Single grain morphologies (Fig. 8B) support interpretations of a limited recycling of Permian-Triassic and Cambrian to Carboniferous sources in the Bird’s Head. The presence of rounded and idiomorphic Proterozoic grains indicates a mix of poly-recycled Australian material and newly uplifted and eroded Australian cratons. Similar age Plover Formation sandstones (Fig. 1B) were deposited at this time in the Malita-Calder Graben. The Babar sandstones could be distal equivalents of them.

No tectonic models (e.g. Metcalfe, 1996; Charlton, 2012) have suggested Jurassic volcanic activity along the northern Australian margin and sources of sediment were assumed to be entirely in continental Australia. However, palaeogeographical reconstructions of the northern Australian continental margin (Barber et al., 2003) interpret fine grained sediments were deposited in the area of the Outer Banda Arc Islands rather than the coarse sandstones actually observed. A

Bird’s Head source for the sandstones resolves this problem. Fig. 14 shows a palaeogeographic map with tectonic elements and major sediment pathways for the Late Jurassic. Suggested sources, including recycled Bird’s Head material, and active volcanism at areas of weakened crust due to initial rifting in the Banda Block are indicated.

6. Conclusions

Most Outer Banda Arc sandstones are compositionally mature but textures indicate an immature character for many of them. Acid igneous and metamorphic sources are common. The rounding of many zircons suggests multiple episodes of sedimentary recycling. Variations along the northwestern Australian margin show that the eastern area (Tanimbar and Babar) is dominated by acid igneous and the western area (Timor) by metamorphic sources.

The Bird’s Head and Sula Spur region are suggested to be previously unrecognized sediment sources from the Triassic onwards. A Western Australian contribution to sandstones in the western islands and a predominantly Central/Northern Australian signal in the eastern islands is interpreted. A local and important Jurassic source in the Timor region is proposed, produced by rift-related volcanic activity north of Timor associated with separation of the Banda blocks from the Australian margin. The provenance of the Triassic and Jurassic sandstones strongly supports an autochthonous Bird’s Head which was in a similar position relative to Australia at least from the Triassic.

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Appendix A. Supplementary data

Supplementary data to this article can be found online. Supplementary Data File 1 contains data tables of modal compositions and textural analyses. Supplementary Data File 2 contains data tables of heavy mineral analyses. Supplementary Data File 3 contains data tables of LA-ICP-MS analyses.

References

Amri, C., Harahap, B.H., Pieters, P.E., Bladon, G.M., 1990. The geology of the Sorong Sheet area, Irian Jaya (parts of quadrangles 2714, 2715, 2814, 2815) Scale 1: 250,000. Geological Survey of Indonesia, Directorate of Mineral Resources, Geological Research and Development Centre, Bandung, 70pp.

Audley-Charles, M.G., 1965. Permian palaeogeography of the northern Australia-Timor region. Palaeogeography, Palaeoclimatology and Palaeoecology 1, 297-305.

Audley-Charles, M.G., 1968. The geology of Portuguese Timor. Geological Society of London, Memoir 4, 76pp.

Baillie, P.W., Fraser, T.H., Hall, R., Myers, K., 2004. Geological development of eastern Indonesia and the northern Australia collision zone: A review. Proceedings of the Timor Sea Symposium, Northern Territory Geological Survey, Darwin Northern Territory, Australia, Special Publication 1, 539-550.

Baldwin, S.L., Ireland, T.R., 1995. The tale of two eras: Pliocene-Pleistocene unroofing of Cenozoic and late Archean zircons from active metamorphic core complexes, Solomon Sea, Papua New Guinea. Geology 23, 1023-1026.

Barber, P., Carter, P., Fraser, T., Baillie, P., Myers, K., 2003. Paleozoic and Mesozoic petroleum systems in the Timor and Arfura Seas, Eastern Indonesia. Indonesian Petroleum Association, Proceedings 29th Annual Convention, Jakarta, 485-500.

Betts, P.G., Giles, D., Lister, G.S., Frick, L.R., 2002. Evolution of the Australian lithosphere. Australian Journal of Earth Sciences 49, 661-695.

Bird, P.R., Cook, S.E., 1991. Permo-Triassic successions of the Kekneno area, West Timor: implications for palaeogeography and basin evolution. Journal of Southeast Asian Earth Sciences 6, 359-372.

Bishop, M.G., 1999. Total petroleum systems of the Bonaparte Gulf Basin area, Australia; Jurassic, Early Cretaceous-Mesozoic; Keyling, Hyland Bay-Permian; Milligans-Carboniferous, Permian. US Dept. of the Interior, US Geological Survey.

Bryan, S.E., Cook, A., Allen, C.M., Siegel, C., Purdy, D., Greentree, J., Uysal, T., 2012. Early-mid Cretaceous tectonic evolution of eastern Gondwana: From silicic LIP magmatism to continental rupture. Episodes 35, 142-152.

Cawood, P.A., Nemchin, A.A., Freeman, M., Sircombe, K., 2003. Linking source and sedimentary basin: Detrital zircon record of sediment flux along a modern river system and implications for provenance studies. Earth and Planetary Science Letters 210, 259-268.

Cawood, P.A., Nemchin, A.A., Leverenz, A., Saeed, A., Ballance, P.F., 1999. U/Pb dating of detrital zircons: Implications for the provenance record of Gondwana margin terranes. Geological Society of America Bulletin 111, 1107-1119.

Charlton, T.R., 1987. The tectonic evolution of the Kolbano-Timor Trough Accretionary Complex, Timor, Indonesia. Ph.D. thesis, University of London.

Charlton, T.R., de Smet, M.E.M., Samodra, H., Kaye, S.J., 1991. The stratigraphic and structural evolution of the Tanimbar islands, eastern Indonesia. Journal of Southeast Asian Earth Sciences 6, 343-358.

Charlton, T.R. 2001. The Permo-Triassic evolution of Gondwanan eastern Indonesia, and the final Mesozoic separation of SE Asia from Australia. Journal of Asian Earth Sciences v.19, p.595-617.

Charlton, T.R. 2012. Permian-Jurassic Palaeogeography of the SE Banda Arc Region. Berita Sedimentologi No. 24, 5-17.

Clements, B., Sevastjanova, I., Hall, R., Belousova, E., Griffin, W., Pearson, N., 2012. Detrital zircon U-Pb age and Hf-isotope perspective on sediment provenance and tectonic models in SE Asia. In: Rasbury, T., Hemming, S., Riggs, N. (Eds.), Mineralogical and Geochemical Approaches to Provenance. Geological Society of America Special Paper 487, pp. 37-61.

Cook, S.E., 1987. Triassic sediments from East Kekneno, West Timor. Ph.D. Thesis, University of London.

Davies, L., Hall, R., Armstrong, R., 2014. Cretaceous Crust in SW Borneo: Petrological, Geochemical and Geochronological Constraints from the Schwaner Mountains. Indonesian Petroleum Association, Proceedings 38th Annual Convention, Jakarta, IPA 14-G-025.

de Roever, W.P., 1940. Geological investigation in the south western Moetis region (Netherlands Timor). In: Geological Expedition of the University of Amsterdam to the Lesser Sunda Islands (Brouwer, H.A., Ed.). North Holland Publishing, 158-197.

Dickinson, W.R., 1988. Provenance and sediment dispersal in relation to paleotectonics and paleogeography of sedimentary basins. In: Kleinspehn, K., Paola, C. (Eds.), New perspectives in basin analysis, Springer Verlag, New York, pp. 3-25.

Dickinson, W.R., Beard, L.S., Brakenridge, G.R., Erjavic, J.L., Ferguson, R.C., Inman, K.F., Knepp, R.A., Lindeberg, F.A., Ryberg, P.T., 1983. Provenance of North American Phanerozoic sandstones in relation to tectonic setting. Geological Society of America Bulletin 94, 222-235.

Dickinson, W.R., Gehrels, G.E., 2009. Use of U–Pb ages of detrital zircons to infer maximum depositional ages of strata: a test against a Colorado Plateau Mesozoic database. Earth and Planetary Science Letters 288, 115-125.

Dickinson, W.R., Suczek, C.A., 1979. Plate tectonics and sandstone composition. American Association of Petroleum Geologists Bulletin 63, 2164-2182.

Ely, K.S., Sandiford, M., Phillips, D., Boger, S.D., 2014. Detrital zircon U–Pb and 40Ar/39Ar hornblende ages from the Aileu Complex, Timor-Leste: provenance and metamorphic cooling history. Journal of the Geological Society 171, 299-309.

Fahrizal, 1993. Geologi dan Stratigrafi Daerah Tepa dan Sekitarnya, P. Babar, Kabupaten Maluku Tenggara, Propinsi Maluku. Skripsi Sarjana Jurusn Teknik Geologi FTM ITB (unpublished).

Fedo, C.M., Sircombe, K.N., Rainbird, R.H., 2003. Detrital zircon analysis of the sedimentary record. Reviews in Mineralogy and Geochemistry 53, 277-303.

Feo-Codecido, G., 1956. Heavy-mineral techniques and their application to Venezuelan stratigraphy. AAPG Bulletin 40, 984-1000.

Ferdian, F., 2012. Provenance of East Sulawesi and Banggai Sula Zircons. Indonesian Petroleum Association, Proceedings 36th Annual Convention, Jakarta, IPA 12-G-044.

Galehouse, J.S., 1971. Point counting. In: Carver, R.E. (Ed.), Procedures in sedimentary petrology, Wiley Interscience, New York, pp. 385-407.

Garzanti, E., Doglioni, C., Vezzoli, G., Ando, S., 2007. Orogenic belts and orogenic sediment provenance. Journal of Geology 115, 315-334.

Gehrels, G., Valencia, V., Pullen, A., 2006. Detrital Zircon Geochronology by Laser Ablation Multicollector ICPMS at the Arizona LaserChron Center. In: Olszewski, T. (Ed.), Geochronology: Emerging Opportunities. Paleontology Society Papers 12, pp. 67-76.

Goldstein, S., Arndt, N.T., Stallard, R.F., 1997. The history of a continent from U-Pb ages of zircons from Orinoco River sand and Sm-Nd isotopes in Orinoco basin river sediments. Chemical Geology 139, 271-286.

Gradstein, F.M., Ogg, G., Schmitz, M., 2012. The Geologic Time Scale 2012. Elsevier.

Gunawan, I., Hall, R. & Sevastjanova, I., 2012. Age, character and provenance of the Tipuma Formation, West Papua: New insights from detrital zircon dating. Proceedings Indonesian Petroleum Association 36th Annual Convention, IPA12-G-027 1-14.

Hall, R., 2012. Late Jurassic-Cenozoic reconstructions of the Indonesian region and the Indian Ocean. Tectonophysics 570, 1-41.

Hall, R., Clements, B., Smyth, H.R., 2009. Sundaland: Basement character, structure and plate tectonic development. Proceedings Indonesian Petroleum Association, 33rd Annual Convention, Jakarta IPA09-G-134 1-27.

Hall, R., Cottam, M.A., Wilson, M.E.J., 2011. The SE Asian gateway: history and tectonics of Australia-Asia collision. In: Hall, R., Cottam, M.A., Wilson, M.E.J.

(Eds.), The SE Asian Gateway: History and Tectonics of the Australia-Asia collision. Geological Society of London Special Publication 355, pp. 1-6.

Hall, R., Sevastjanova, I., 2012. Australian crust in Indonesia. Australian Journal of Earth Sciences 59, 827-844.

Hamilton, W., 1979. Tectonics of the Indonesian region. U.S.G.S. Prof. Paper 1078, 345 pp.

Hennig, J., Hall, R., Armstrong, R.A., 2016. U-Pb zircon geochronology of rocks from west Central Sulawesi, Indonesia: Extension-related metamorphism and magmatism during the early stages of mountain building. Gondwana Research 32, 41–63.

Hill, K.C., Hall, R., 2003. Mesozoic-Cenozoic evolution of Australia's New Guinea margin in a west Pacific context. Geological Society of America Special Papers 372, 265-290.

Housh, T., McMahon, T.P., 2000. Ancient isotopic characteristics of Neogene potassic magmatism in western New Guinea (Irian Jaya, Indonesia). Lithos 50, 217-239.

Ingersoll, R.V., Fullard, T.F., Ford, R.L., Grimm, J.P., Pickle, J.D., Sares, S.W., 1984. The effect of grain size on detrital modes; a test of the Gazzi-Dickinson point-counting method. Journal of Sedimentary Research 54, 103-116.

Jasin, B., Haile, N. 1996. Uppermost Jurassic-Lower Cretaceous radiolarian chert from the Tanimbar Islands (Banda Arc), Indonesia. Journal of Southeast Asian Earth Sciences 14, 91-100.

Kwon, C.W., Kim, S.W., Park, S.I., Park, J., Oh, J.H., Kim, B.C., Koh, H.J., Cho, D.L., 2014. Sedimentological characteristics and new detrital zircon SHRIMP

U–Pb ages of the Babulu Formation in the Fohorem area, Timor-Leste. Australian Journal of Earth Sciences 61, 865-880.

Lewis, C.J., Sircombe, K., 2013. Use of U-Pb geochronology to delineate provenance of North West Shelf sediments, Australia. In: M., K., S.J, M. (Editors), The Sedimentary Basins of Western Australia, Perth, WA.

Mange, M.A., 2002. New look at heavy minerals - a short course. 16th International Sedimentological Congress, Rand Afrikaans University, South Africa, 34 pp.

Mange, M.A., Maurer, H.F.W., 1992. Heavy minerals in colour. Chapman & Hall, London, 147 pp.

Metcalfe, I., 1996. Pre-Cretaceous Evolution of SE Asian Terranes. In: Hall, R., Blundell, D.J. (Eds.), Tectonic Evolution of SE Asia. Geological Society of London Special Publication 106, pp. 97-122.

Morton, A.C., 1986. Dissolution of apatite in North Sea Jurassic sandstones: implications for the generation of secondary porosity. Clay Minerals 21, 711-733.

Murphy, J.B., Fernández-Suárez, J., Keppie, J.D., Jeffries, T.E., 2004. Contiguous rather than discrete Paleozoic histories for the Avalon and Meguma terranes based on detrital zircon data. Geology 32, 585-588.

Myers, J.S., Shaw, R.D., Tyler, I.M., 1996. Tectonic evolution of Proterozoic Australia. Tectonics 15, 1431-1446.

Nichols, G., 2009. Sedimentology and stratigraphy. John Wiley & Sons.

Park, S.-I., Kwon, S., Kim, S.W., 2014. Evidence for the Jurassic arc volcanism of the Lolotoi complex, Timor: Tectonic implications. Journal of Asian Earth Sciences 95, 254-265.

Pearce, N.J.G., Perkins, W.T., Westgate, J.A., Gorton, M.P., Jackson, S.E., Neal, C.R., Chenery, S.P., 1997. A compilation of new and published major and trace element data for NIST SRM 610 and NIST SRM 612 glass reference materials. Geostandards Newsletter 21, 115-144.

Pieters, P.E., Hartono, U., Amri, C., 1989. Geologi lembar Mar, Irian Jaya. Geological Survey of Indonesia, Directorate of Mineral Resources, Geological Research and Development Centre, Bandung, 62 pp.

Pieters, P.E., Pigram, C.J., Trail, D.S., Dow, D.B., Ratman, N., Sukamto, R., 1983. The stratigraphy of western Irian Jaya. Indonesian Petroleum Association, Proceedings 12th Annual Convention, Jakarta, 229-262.

Pieters, P.E., Supriatna, S., 1990. Late-Cretaceous-Early Tertiary continent-continent collision in Borneo. In: Wiley, T.J., Howell, D.G., Wong, F.L. (Eds.), Terrane Analysis of China and the Pacific Rim. Circum Pacific Council for Energy and Mineral Resources, Earth Science Series 13, pp. 193-194.

Pigram, C.J., Panggabean, H., 1984. Rifting of the northern margin of the Australian continent and the origin of some microcontinents in eastern Indonesia. Tectonophysics 107, 331-353.

Pigram, C.J., Surono, S., J.B., 1985. Origin of the Sula Platform, eastern Indonesia. Geology 13, 246-248.

Pigram, C.J., Symonds, P.A., 1991. A review of the timing of the major tectonic events in the New Guinea Orogen. Journal of Southeast Asian Earth Sciences 6, 307-318.

Richardson, A., 1993. Lithosphere structure and dynamics of the banda Arc collision zone, Eastern Indonesia. Bulletin of the Geological Society of Malaysia 33, 105-118.

Robinson, G.P., Ryburn, R.J., Harahap, B.H., Tobing, S.L., Achdan, A., Bladon, G.M., Pieters, P.E., 1990. Geology of the Steenkool sheet area, Irian Jaya. Geological Survey of Indonesia, Directorate of Mineral Resources, Geological Research and Development Centre, Bandung.

Sawyer, R.K., Sani, K., Brown, S., 1993. The stratigraphy and sedimentology of West Timor, Indonesia. Indonesian Petroleum Association, Proceedings 22nd annual convention, Jakarta, 533-574.

Schoene, B., 2014. 4.10 - U–Th–Pb Geochronology, Treatise on Geochemistry (Second Edition), Elsevier, Oxford, pp. 341-378.

Sevastjanova, I., Clements, B., Hall, R., Belousova, E., Pearson, N., Griffin, W., 2010. Detrital Zircon U-Pb and Hf-isotope Constrains on Basement Ages, Granitic Magmatism, and Sediment Provenance in the Malay Peninsula. EGU General Assembly Conference Abstracts, 12, 11191.

Sevastjanova, I., Clements, B., Hall, R., Belousova, E.A., Griffin, W.L., Pearson, N., 2011. Granitic magmatism, basement ages, and provenance indicators in the Malay Peninsula: Insights from detrital zircon U-Pb and Hf-isotope data. Gondwana Research 19, 1024-1039.

Sevastjanova, I., Hall, R., Alderton, D., 2012. A detrital heavy mineral viewpoint on sediment provenance and tropical weathering in SE Asia. Sedimentary Geology 280, 179-194.

Sevastjanova, I., Hall, R., Rittner, M., Paw, S.M.T.L., Naing, T.T., Alderton, D.H., Comfort, G., 2016. Myanmar and Asia united, Australia left behind long ago. Gondwana Research 32, 24-40.

Sircombe, K.N., Freeman, M.J., 1999. Provenance of detrital zircons on the Western Australian coastline-Implications for the geological history of the Perth basin and denudation of the Yilgarn craton. Geology 27, 879-882.

Sláma, J., Košler, J., Condon, D.J., Crowley, J.L., Gerdes, A., Hanchar, J.M., Horstwood, M.S.A., Morris, G.A., Nasdala, L., Norberg, N., Schaltegger, U., Schoene, B., Tubrett, M.N., Whitehouse, M.J., 2008. Plešovice zircon — A new natural reference material for U–Pb and Hf isotopic microanalysis. Chemical Geology 249, 1-35.

Smyth, H., Hall, R., Hamilton, J., Kinny, P., 2003. Volcanic origin of quartz-rich sediments in East Java. Indonesian Petroleum Association, Proceedings 29th Annual Convention, Jakarta, 541-559.

Smyth, H.R., Hall, R., Nichols, G.J., 2008. Significant volcanic contribution to some quartz-rich sandstones, east Java, Indonesia. Journal of Sedimentary Research 78, 335-356.

Smyth, H.R., Hamilton, P.J., Hall, R., Kinny, P.D., 2007. The deep crust beneath island arcs: inherited zircons reveal a Gondwana continental fragment beneath East Java, Indonesia. Earth and Planetary Science Letters 258, 269-282.

Southgate, P., Sircombe, K.N., Lewis, C.J., 2011. New insights into reservoir sand provenance in the Exmouth Plateau and Browse Basin. APPEA Perth, Western Australia.

Spencer, C.J., Harris, R.A., Major, J.R., Provenance of Permian–Triassic Gondwana Sequence units accreted to the Banda Arc in the Timor region: Constraints from zircon U–Pb and Hf isotopes. Gondwana Research doi:10.1016/j.gr.2015.10.012.

Struckmeyer, H.I.M., Yeung, M., Pigram, C.J., 1993. Mesozoic to Cainozoic plate tectonic and palaeogeographic evolution of the New Guinea region. Petroleum Exploration and Development in Papua New Guinea, Port Moresby. Proceedings of 2nd PNG Petroleum Convention, 261-290.

Sukamto, R., Westermann, G.E.G., 1993. Indonesia and Papua New Guinea. In: Westermann, G.E.G. (Ed.), The Jurassic of the Circum-Pacific, Cambridge University Press, pp. 181-193.

Suparman, M., Agustiyanto, D., Achan, A., 1987. Geologic map of the Babar quadrangle, southeast Maluku scale 1 : 250,000. Geological Research and Development Centre, Bandung.

van Bemmelen, R.W., 1949. The Geology of Indonesia. Goverment Printing Office, Nijhoff, The Hague (2nd edition, 1970), 732 pp.

van Hattum, M.W.A., Hall, R., Pickard, A.L., Nichols, G.J., 2006. Southeast Asian sediments not from Asia: Provenance and geochronology of north Borneo sandstones. Geology 34, 589-592.

van Hattum, M.W.A., Hall, R., Pickard, A.L., Nichols, G.J., 2013. Provenance and geochronology of Cenozoic sandstones of northern Borneo. Journal of Asian Earth Sciences 76, 266-282.

Van Wyck, N., Williams, I.S., 2002. Age and provenance of basement metasediments from the Kubor and Bena Bena Blocks, central Highlands, Papua New Guinea: constraints on the tectonic evolution of the northern Australian cratonic margin*. Australian Journal of Earth Sciences 49, 565-577.

Wanner, J., 1913. Geologie von West Timor. Geologische Rundschau 4, 136-50.

Zobell, E.A., 2007. Origin and tectonic evolution of Gondwana sequence units accreted to the Banda Arc: a structural transect through central East Timor. Theses and Dissertations. Brigham Young University.

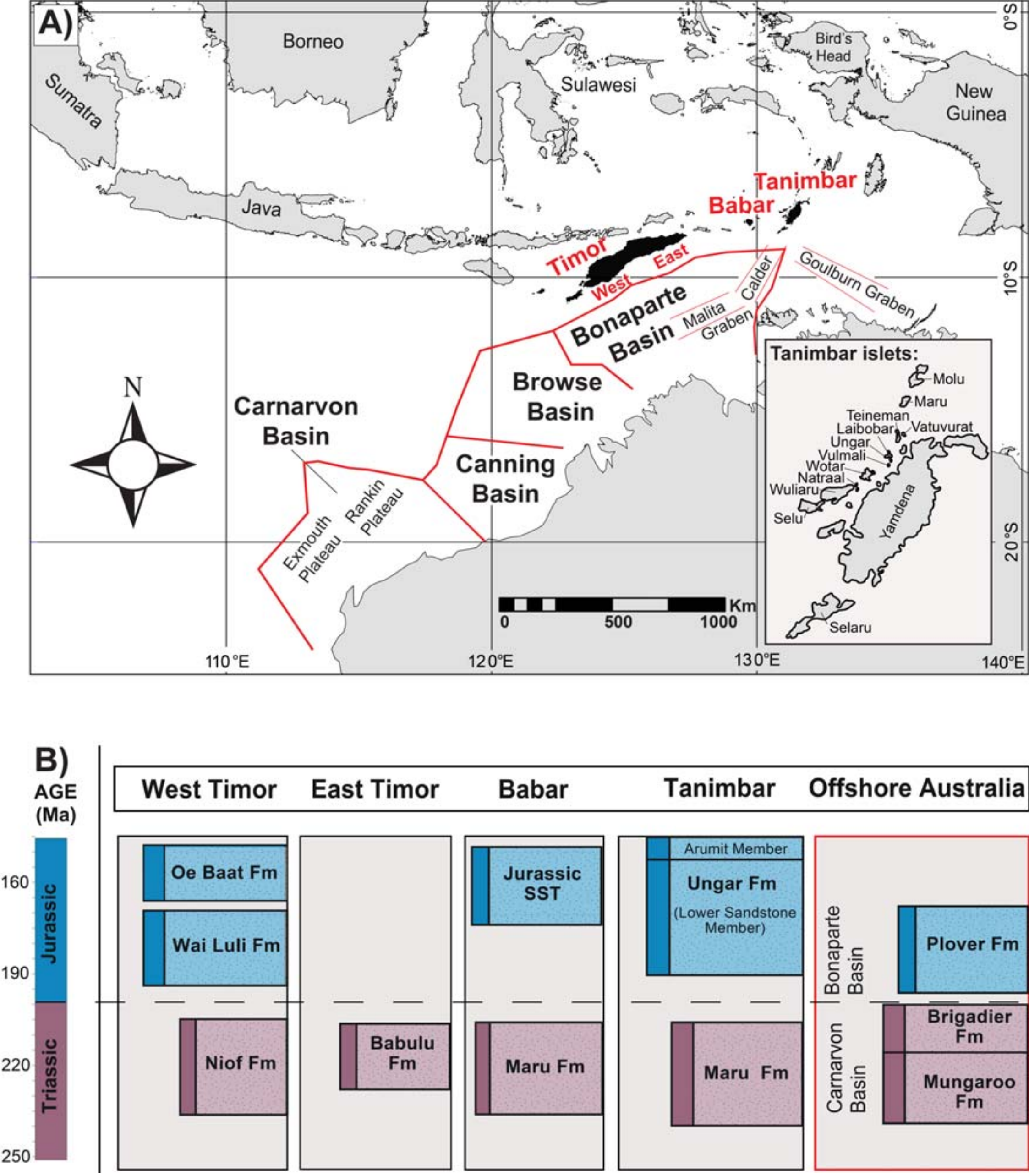

Fig. 1: A) Map of the Banda Arc Islands and Australia that shows main sedimentary offshore basins with selected sub-basins along the NW Shelf. B) Simplified Triassic and Jurassic stratigraphy for Timor, Babar, Tanimbar and selected formations from offshore Australia (Fm=Formation).

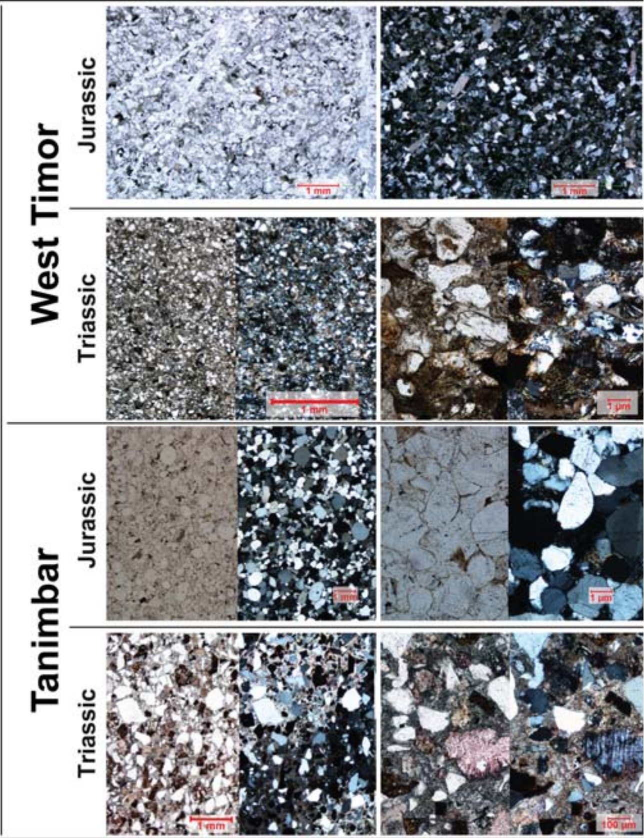

Fig. 2: Representative microphotographs of Triassic and Jurassic sandstones in West Timor and Tanimbar (PPL: plane polarised light; XPL: cross polarised light).

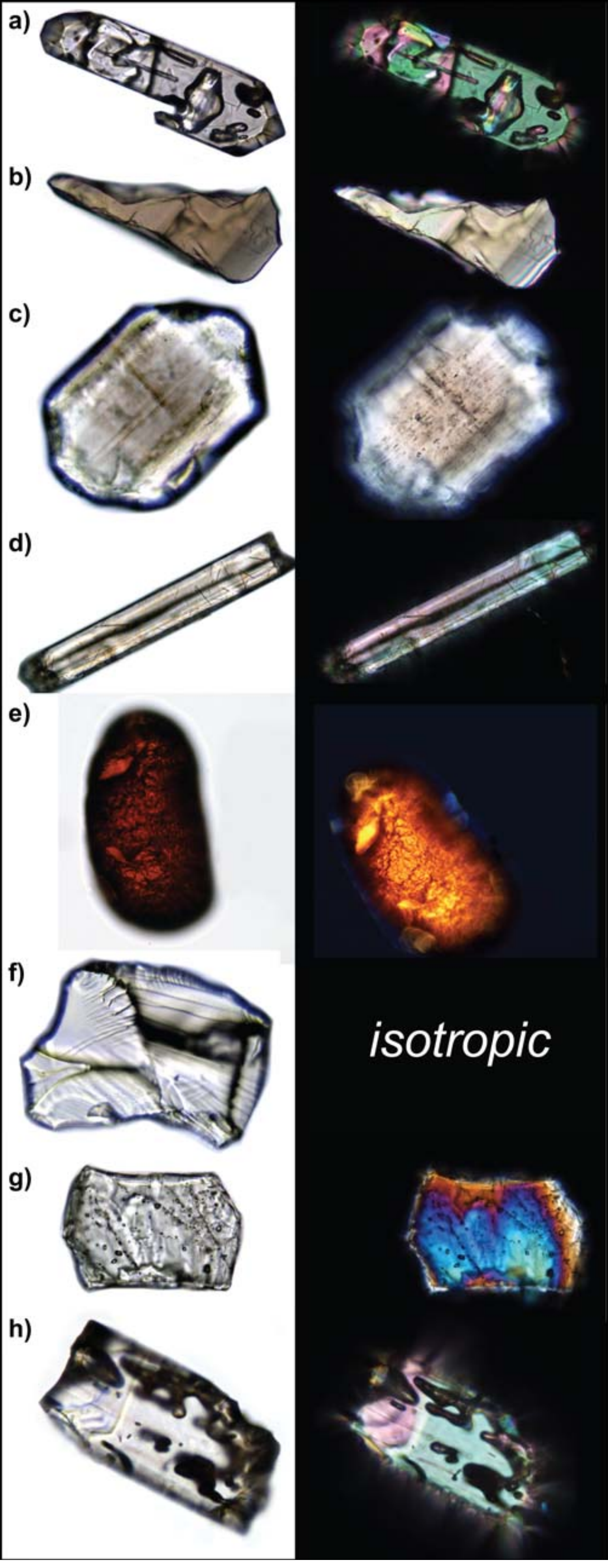

Fig. 3: Example photographs and SEM-images of common heavy minerals in the Banda Arc sandstones: a) zircon; b) tourmaline; c) apatite; d) hypersthene; e) rutile; f) garnet; g) andalusite; h) sillimanite.

Fig. 4: Examples of different categories of zircon morphologies in the Banda Arc. On the left are microscope photographs, on the right SEM photographs that show surface and rounding in detail.

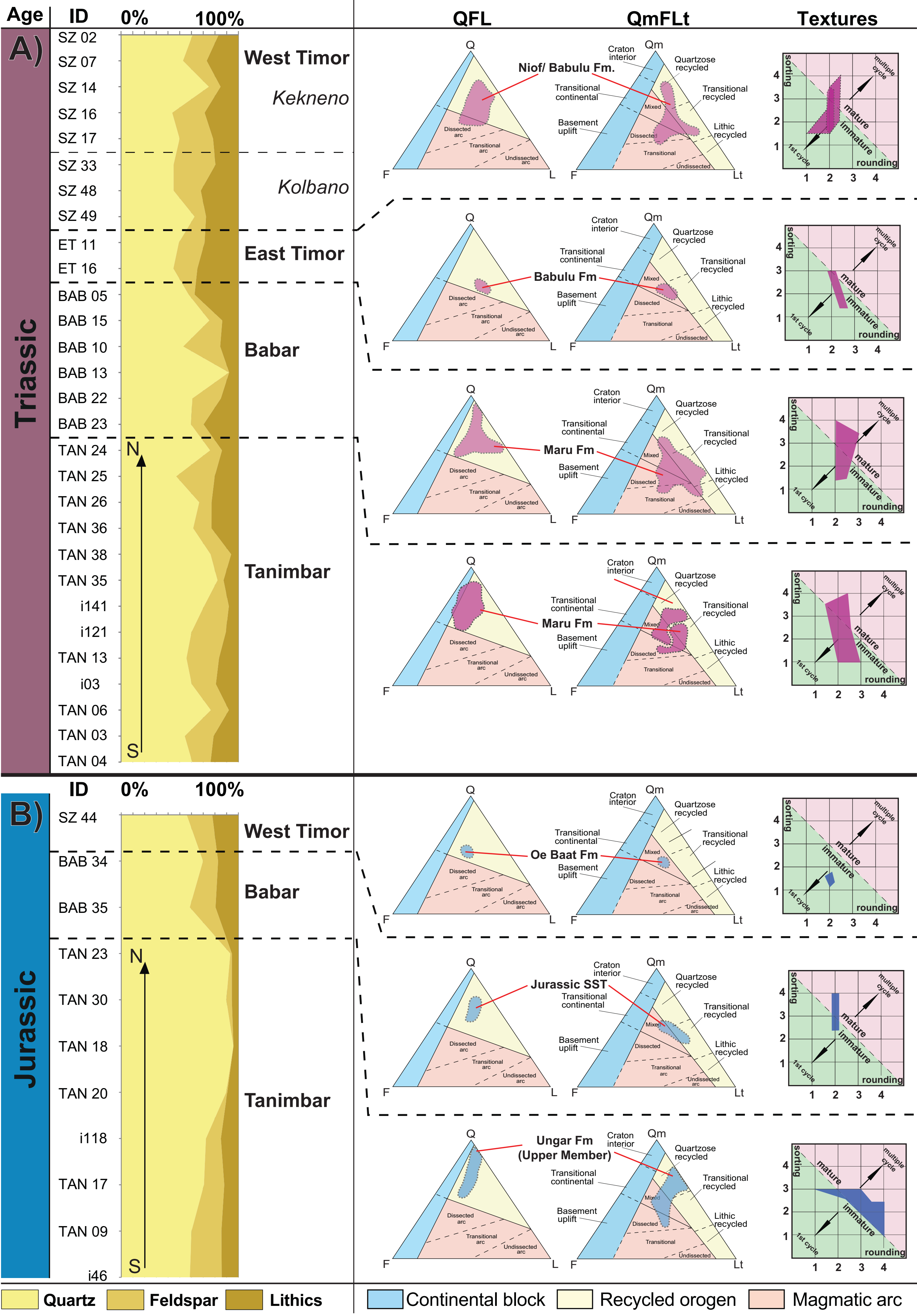

Fig. 5: Overview of point counting analysis of sandstones from the various islands for the Triassic (A) and the Jurassic (B). Ternary plots after Dickinson (1987) indicate possible provenance affiliation (Q – Quartz, F – Feldspar, L – Lithic fragments, Qm – Monocrystalline quartz, Lt – Total lithic fragments). Simplified comparisons between sorting and rounding were used to estimate maturity.

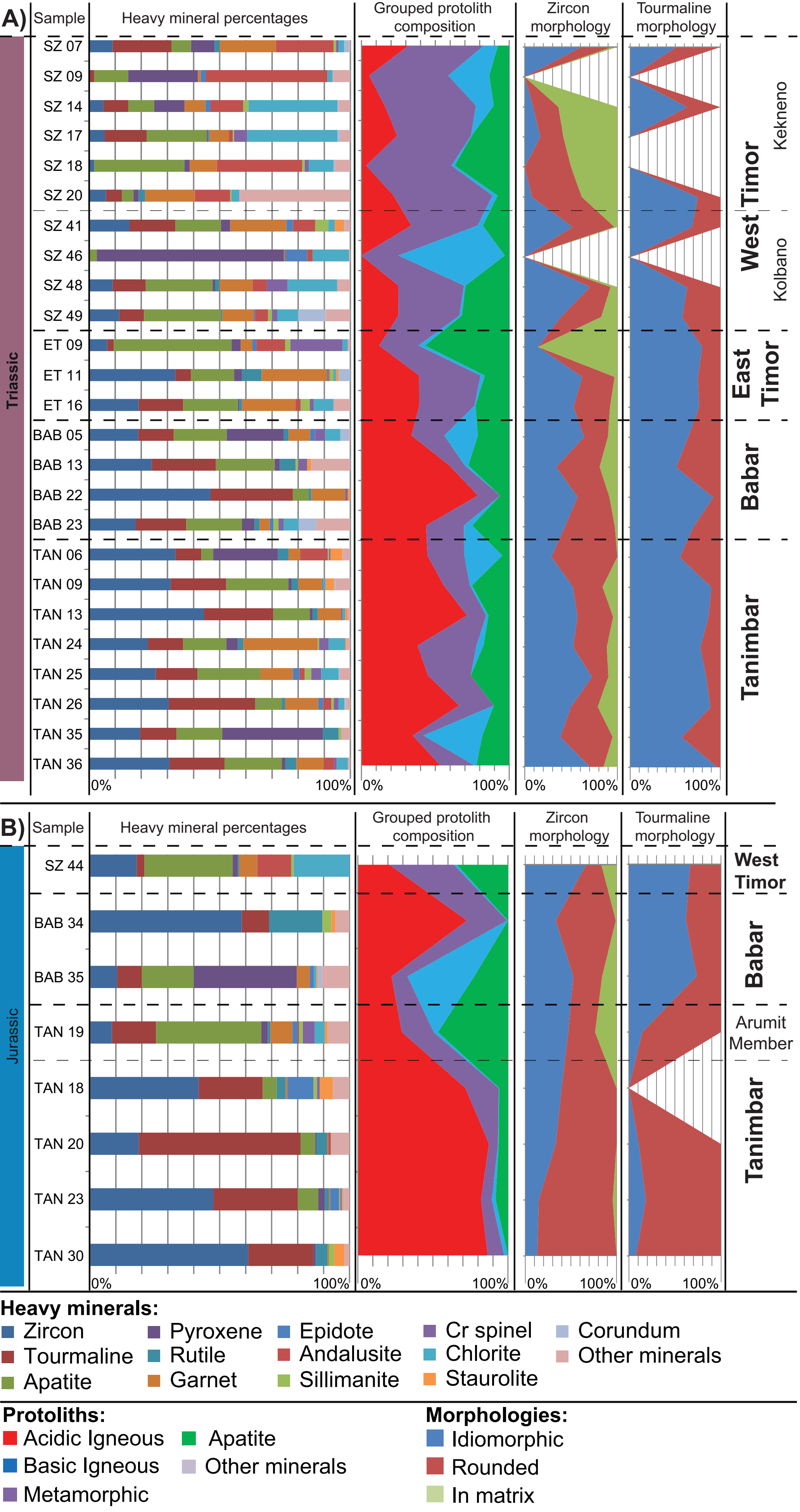

Fig. 6: Overview of heavy mineral percentages, interpreted protoliths and varietal morphology of sandstones from the various islands for the Triassic (A) and the Jurassic (B).

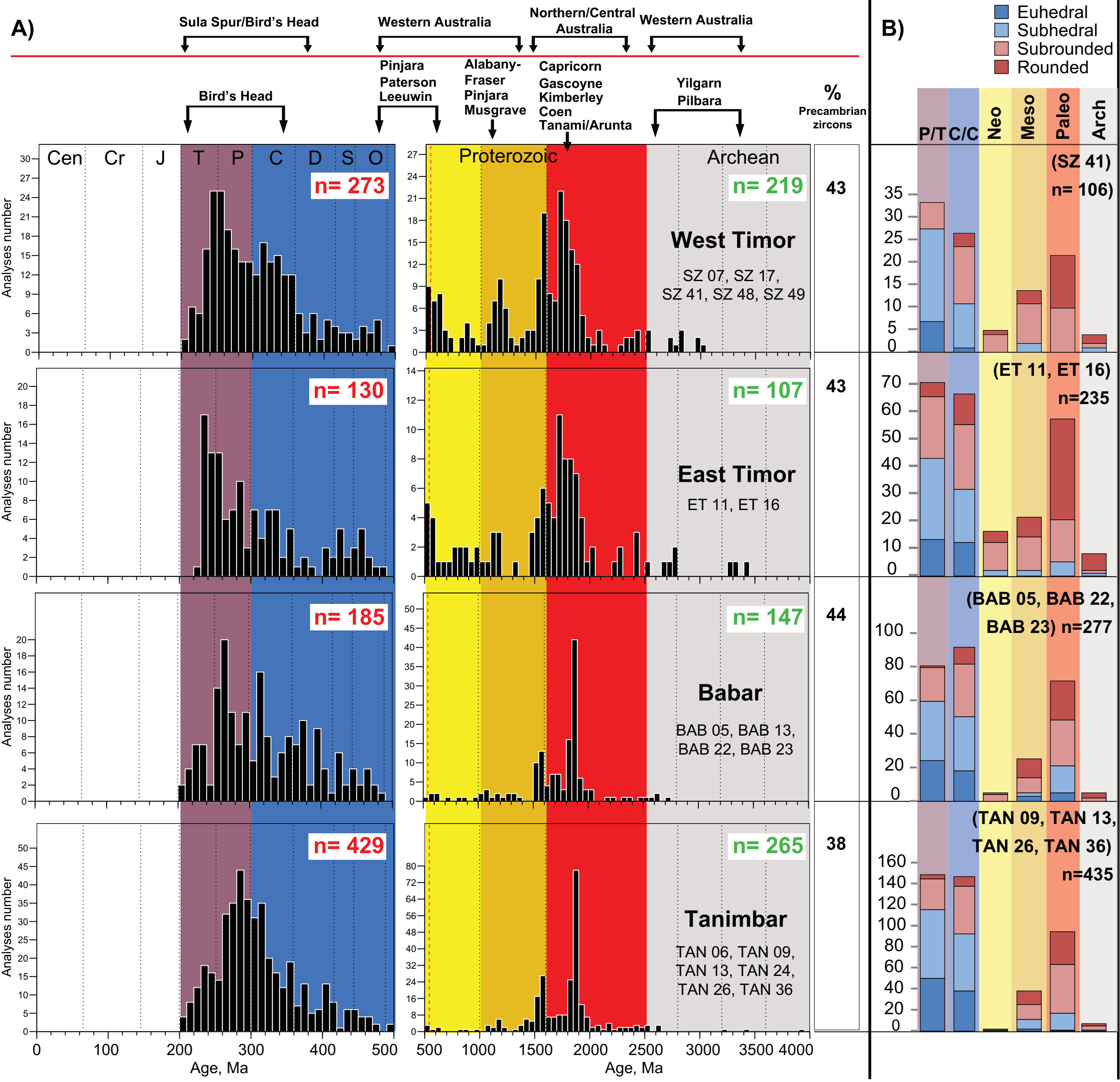

Fig. 7: A) Histograms showing zircon ages for grouped Triassic formations in the Banda Arc with possible sources. Bin width on the left (0-500 Ma) is 10 Ma, on the right (500-4000 Ma) is 50 Ma. Total numbers of zircons for each group are highlighted (red indicates the dominant population, green the smaller). Percentages of Precambrian zircon grains that are older than 541 Ma are indicated; B) Grouped selected samples showing zircon morphology groups and different ages (P/T=Permian-Triassic, C/C=Cambrian-Carboniferous, Neo=Neoproterozoic, Meso=Mesoproterozoic, Paleo= Paleoproterozoic, Arch= Archean).

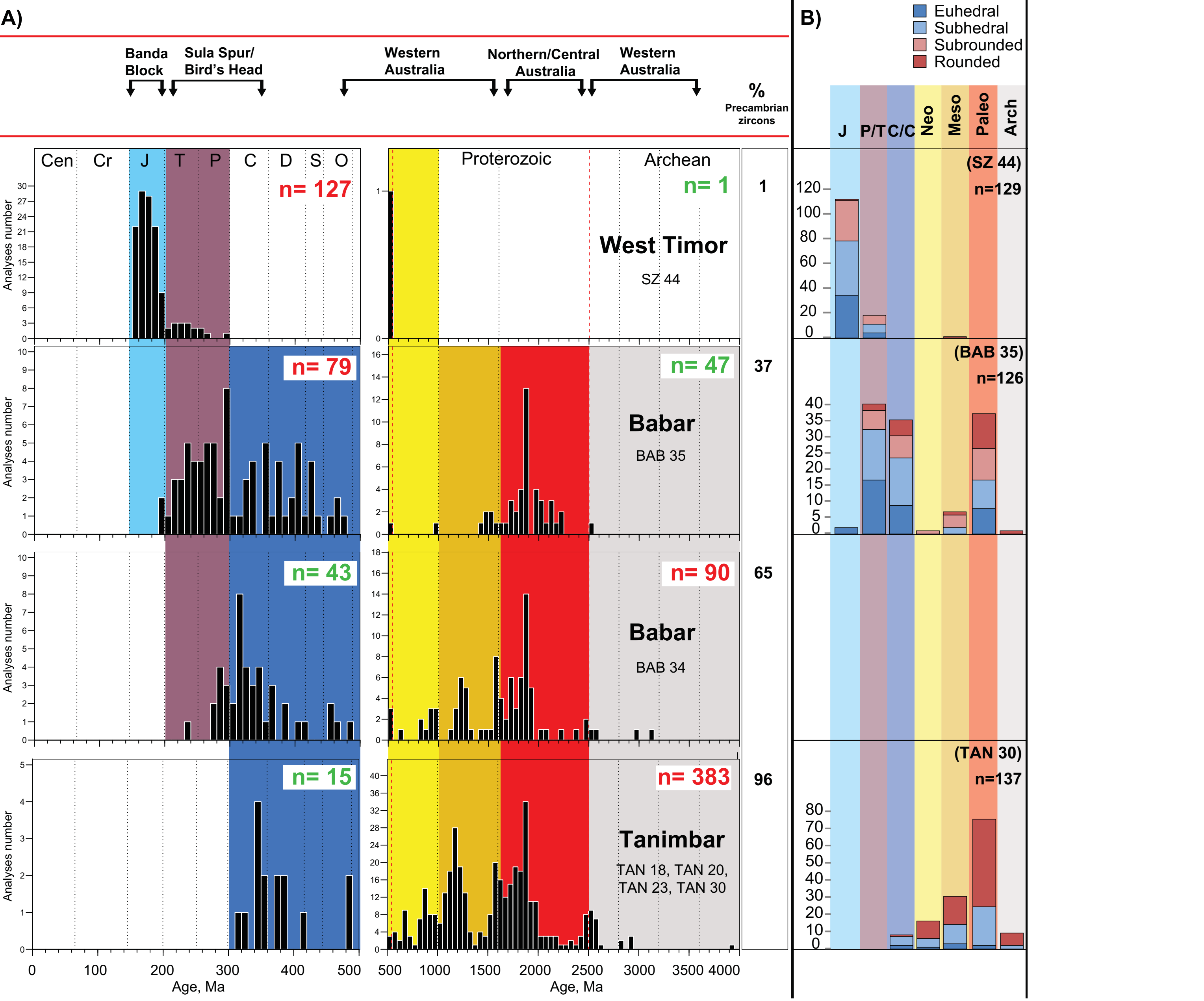

Fig. 8: A) Histograms showing zircon ages for grouped Jurassic formations in the Banda Arc with possible sources. Bin width on the left (0-500 Ma) is 10 Ma, on the right (500-4000 Ma) is 50 Ma. Total numbers of zircons for each group are highlighted (red indicates the dominant population, green the smaller). Percentages of Precambrian zircon grains that are older than 541 Ma are indicated; B) Grouped selected samples showing zircon morphology groups and different ages (P/T=Permian-Triassic, C/C=Cambrian-Carboniferous, Neo=Neoproterozoic, Meso=Mesoproterozoic, Paleo= Paleoproterozoic, Arch= Archean).

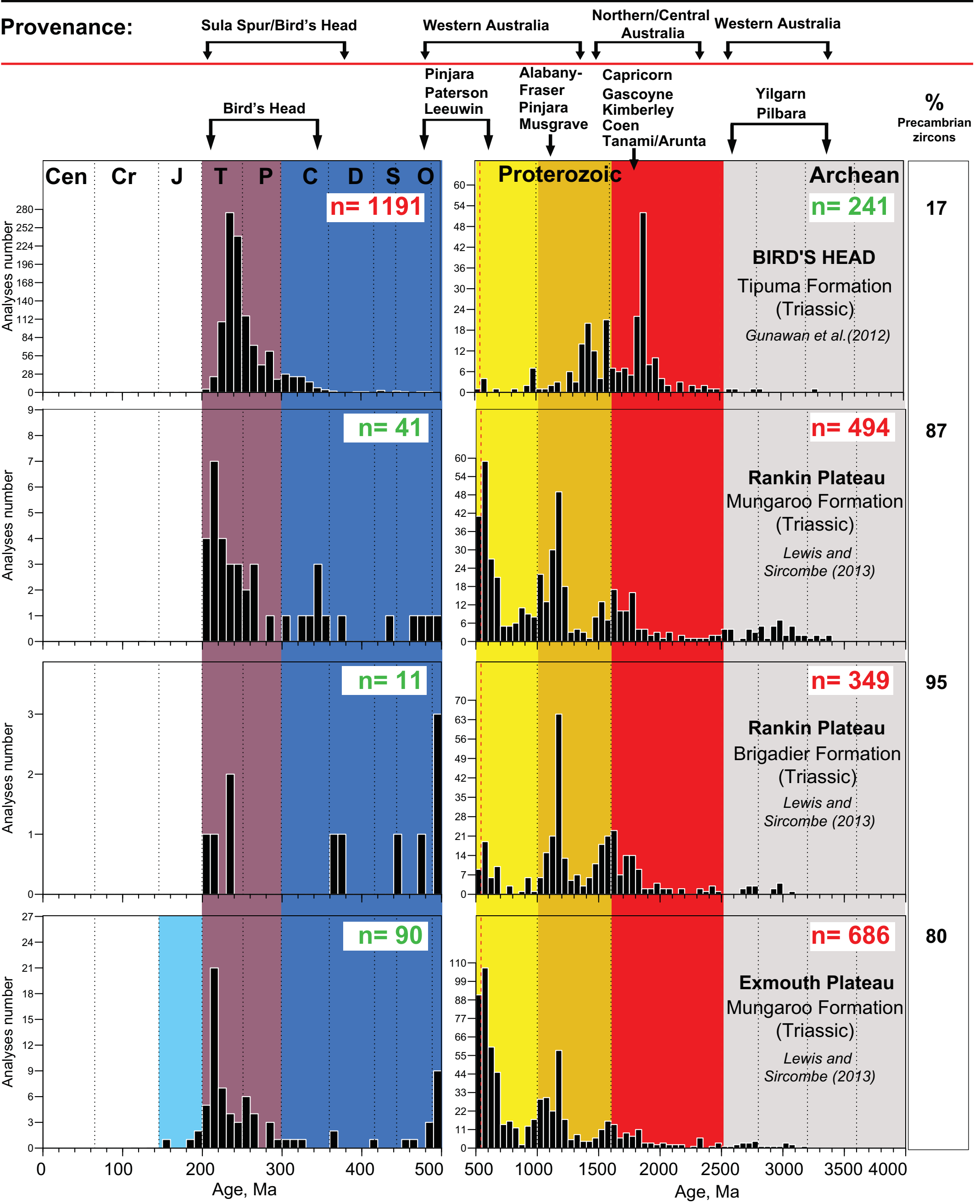

Fig. 9: Histograms showing zircon ages for grouped Triassic formations in the Bird's Head and offshore Australia with possible sources. Bin width on the left (0-500 Ma) is 10 Ma, on the right (500-4000 Ma) is 50 Ma. Total numbers of zircons for each group are highlighted (red indicates the dominant population, green the smaller). Percentages of Precambrian zircon grains that are older than 541 Ma are indicated.

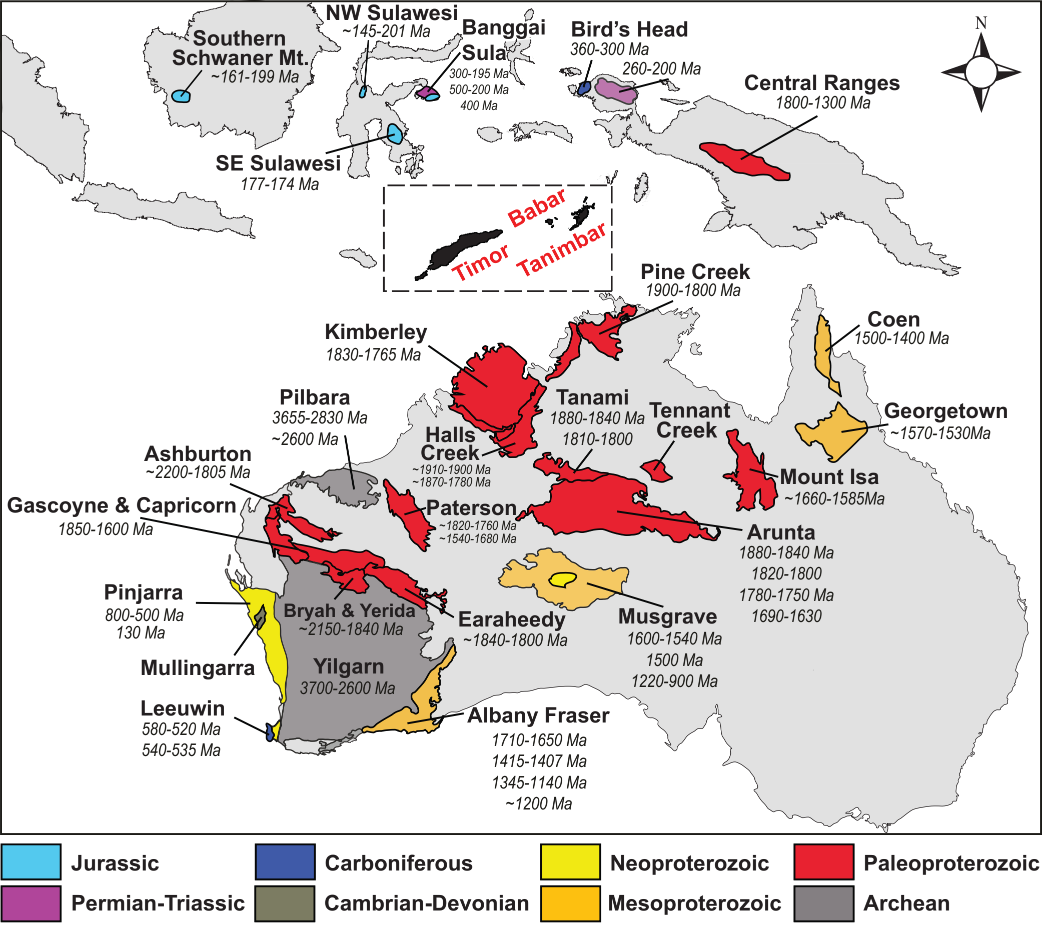

Fig. 10: Simplified overview of various source areas with ages that resemble age populations found in the Banda Arc Islands and the NW Shelf of Australia (major Precambrian terranes modified from Myers et al., 1996; Betts et al. 2002). Major cratons, complexes and formations are indicated, showing the most common age populations. U-Pb and K-Ar ages are from literature discussed in the text and further data by Baldwin and Ireland (1995), Housh and McMahon (2000), Van Wyck and Williams (2002), Pieters et al. (1983), Pieters et al. (1989), Amri et al. (1990), Pieters and Supriatna (1990), Robinson et al. (1990) and Ferdian et al. (2012).

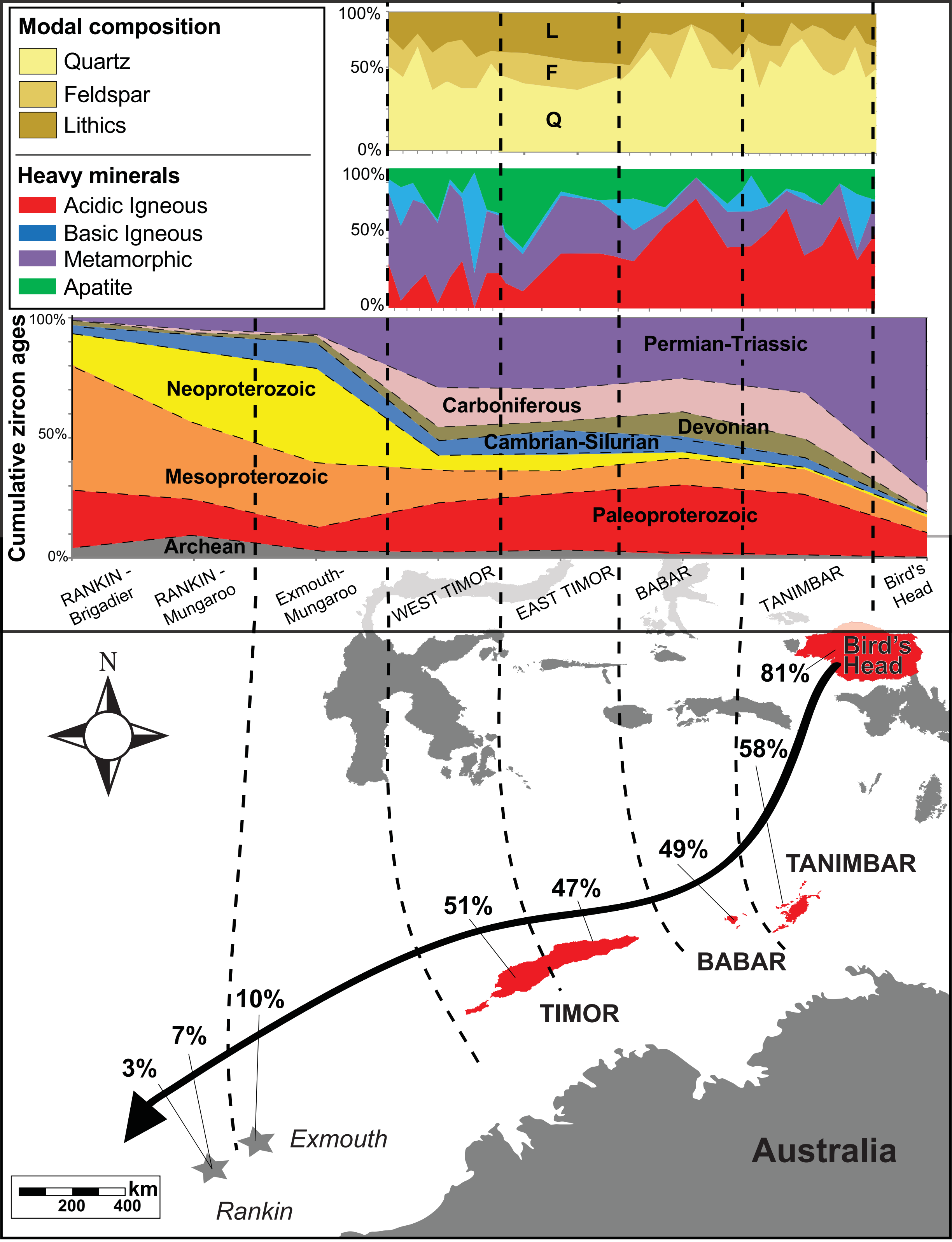

Fig. 11: Overview of modal compositions, heavy mineral assemblages and zircon ages in Triassic sandstones. Percentage values along the arrow indicate the total percentage of Permian-Triassic, Carboniferous and Devonian zircons in the grouped samples from different areas. The values are interpreted to indicate a decrease in zircons derived from the Bird’s Head from east to west.

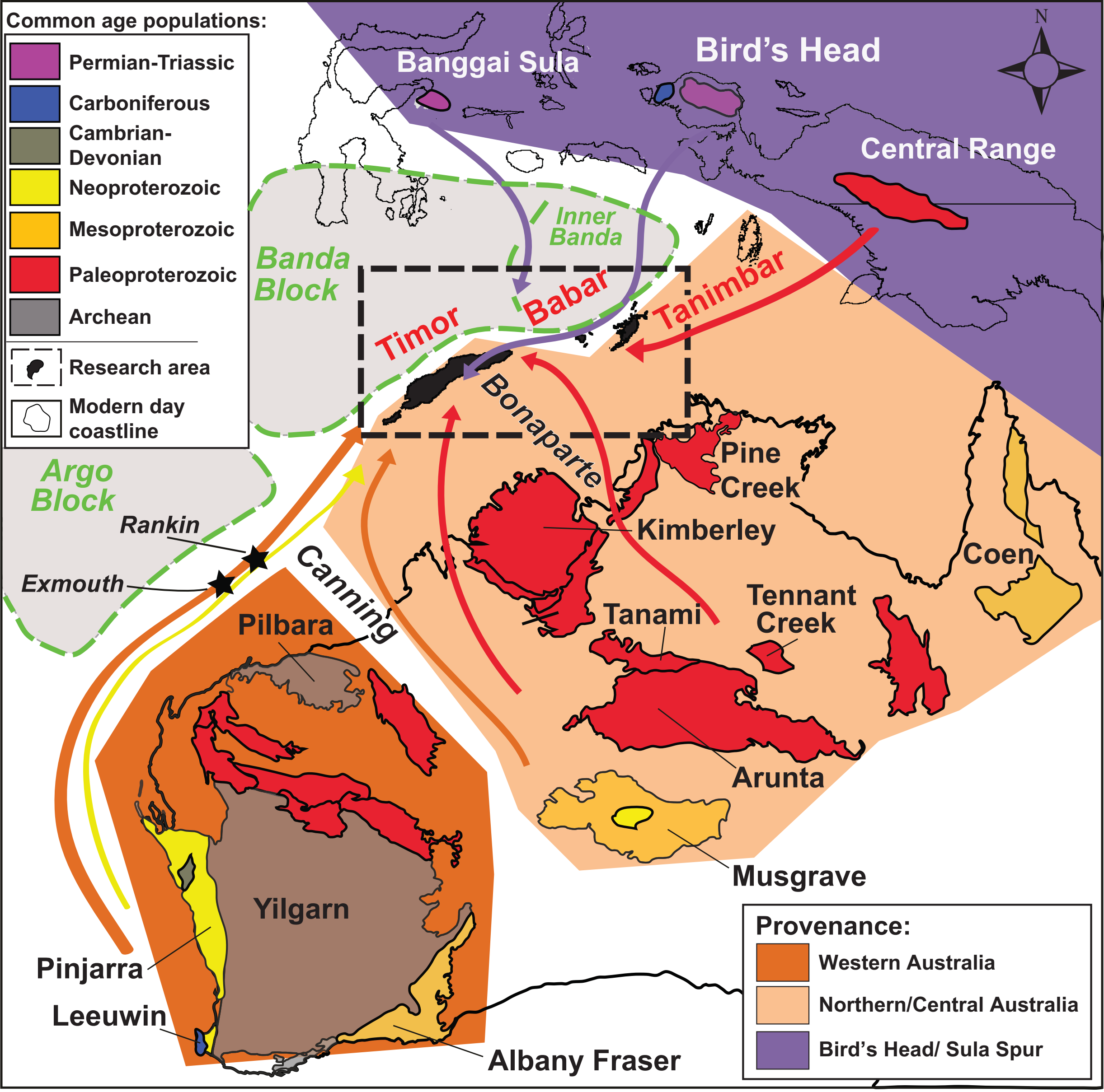

Fig. 12: Triassic palaeogeographic reconstruction with tectonic elements and age provinces with major interpreted sediment transport directions showing suggested sources. The provenance features suggest three principal source areas – Western Australia, Northern/Central Australia and Bird's Head/Sula Spur.

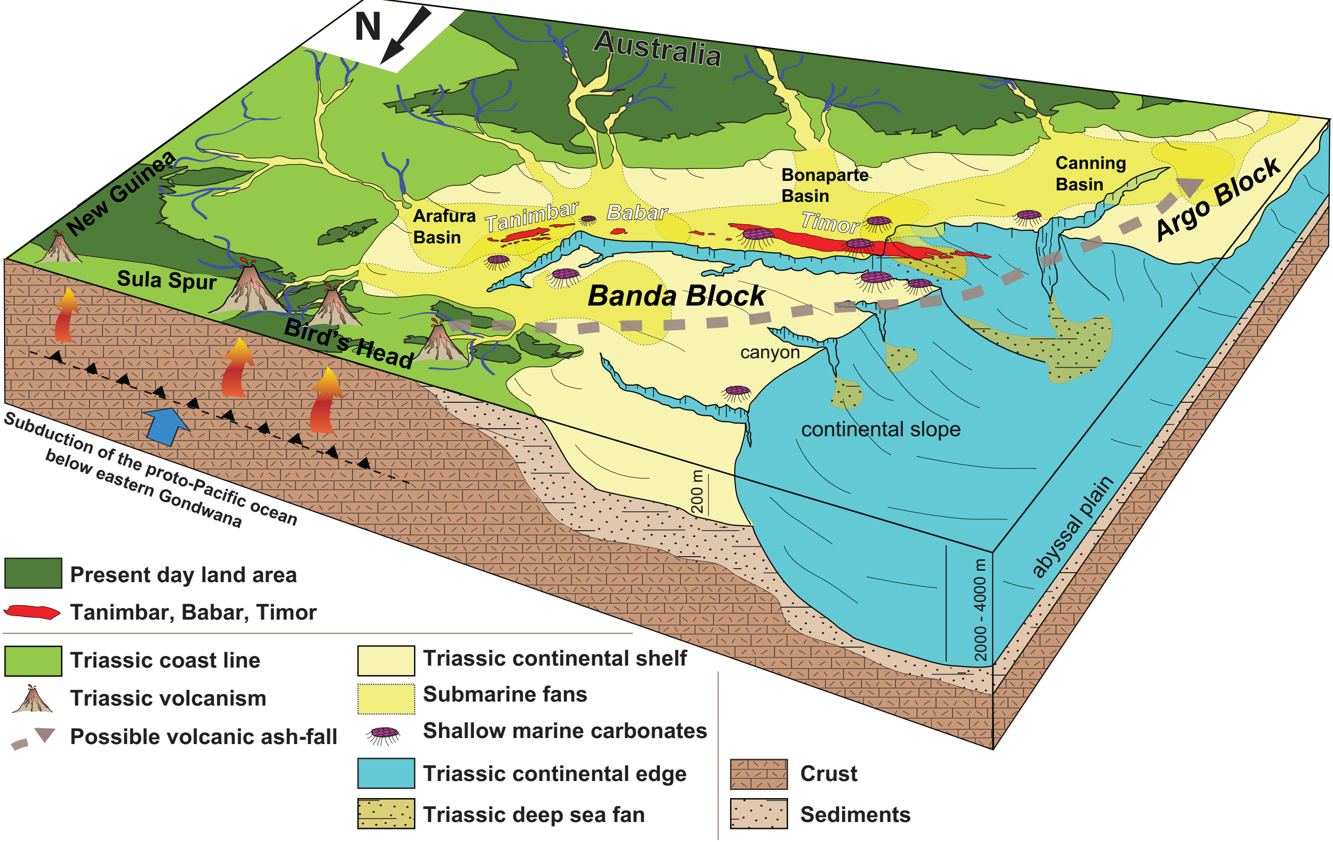

Fig. 13: Simplified three-dimensional cartoon of the greater Banda Arc area in the Triassic. Possible depositional environments and facies are shown. Locations of potential sources are indicated.

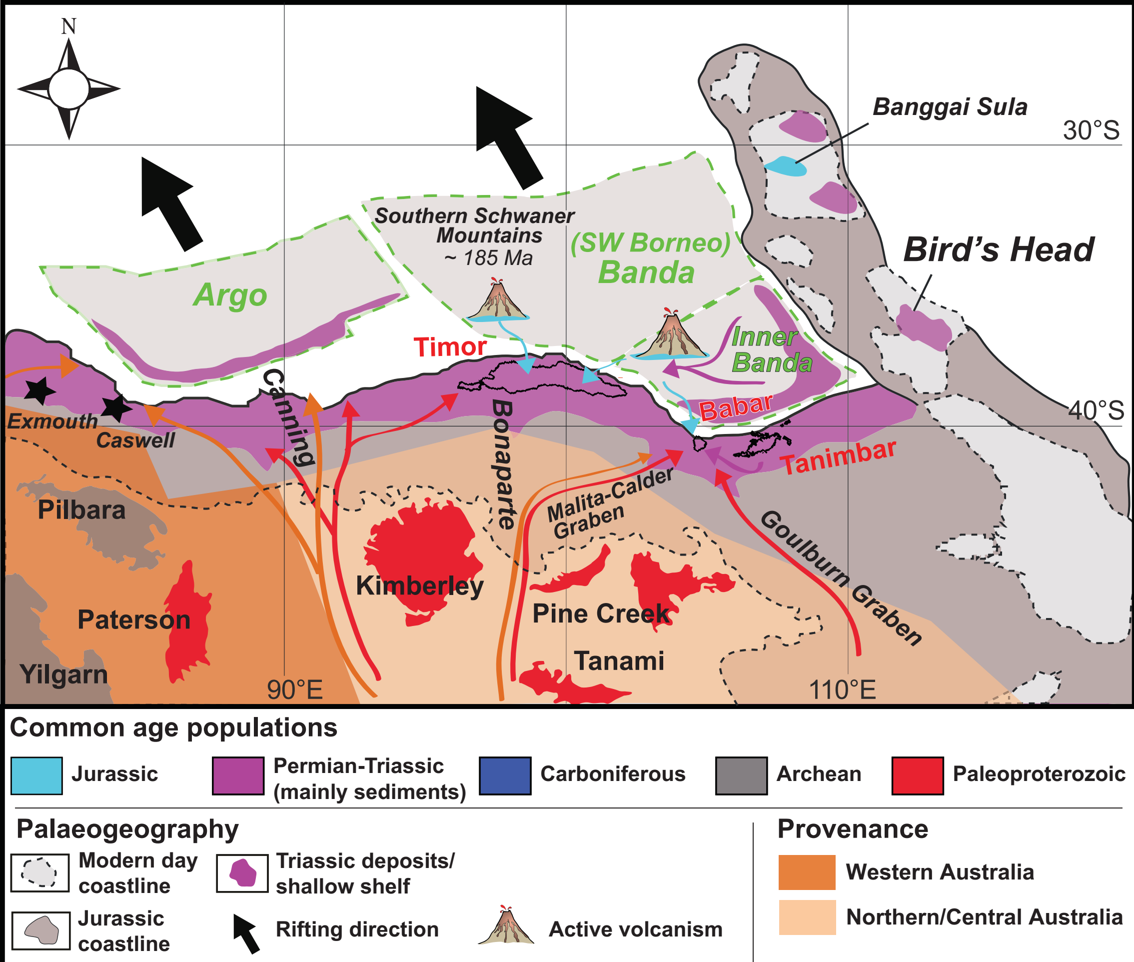

Fig. 14: Simplified palaeogeographic map with tectonic elements and major sediment transport directions for the Late Jurassic. Suggested sources are indicated. The provenance features suggest three principal source areas – Western Australia, Northern/Central Australia and Bird's Head/Sula Spur.